Pottery Analysis

A SOURCEBOOK, SECOND EDITION

Prudence M. Rice

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A Sourcebook, Second Edition

Prudence M. Rice

The University of Chicago Press
Chicago and London

Prudence M. Rice was distinguished professor, department chair, and associate vice chancellor for research at Southern Illinois University Carbondale before retiring in 2011. Her twelve books include *Vintage Moquegua* and *Space-Time Perspectives in Early Colonial Moquegua*.

The University of Chicago Press, Chicago 60637
The University of Chicago Press, Ltd., London
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Printed in the United States of America

24 23 22 21 20 19 18 17 16 15 1 2 3 4 5

ISBN-13: 978-0-226-92320-8 (cloth)
ISBN-13: 978-0-226-92321-5 (paper)
ISBN-13: 978-0-226-92322-2 (e-book)
DOI: 10.7208/chicago/9780226923222.001.0001

Library of Congress Cataloging-in-Publication Data
Rice, Prudence M., author
Pottery analysis : a sourcebook / Prudence M. Rice. — Second edition.
pages cm
Includes bibliographical references and index.
ISBN 978-0-226-92320-8 (cloth : alkaline paper) — ISBN 978-0-226-92321-5 (paperback : alkaline paper) — ISBN 978-0-226-92322-2 (e-book) 1. Pottery—History. 2. Pottery—Expertising. 3. Pottery—Analysis. 4. Ceramics. I. Title.
NK3780.R53 2015
666′.39—dc23

2014042601

♾ This paper meets the requirements of ANSI/NISO Z39.48–1992 (Permanence of Paper).

In memory of Ralph, who was always on top of everything . . .
his worthy successors Lucy, Oliver, Ralston, Bosworth, and Duner . . .
and the current cadre: Poodie, Binz, Teddie, Schroeder,
and especially Harley and Spud sprawling on my desk.
Exceptionally fine pussycats, all.

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Preface to the Second Edition

I begin this second edition of *Pottery Analysis* with a personal note about how (more or less) I got here. My interest in pottery began more than forty years ago while working on my master's thesis, an analysis of previously excavated artifacts from a rock shelter in North Carolina. To try to make sense of the nasty little crumbs of pottery sullenly eyeing me, I perused Anna Shepard's masterful *Ceramics for the Archaeologist* (probably the 1965 printing). And I had an epiphany, an Aha! moment: I learned that the red color of my sherds was caused by iron in the original clay. This discovery completely captured my imagination. Since then, I have been fascinated by the many ways to explore the properties of pottery and their complex relations with raw clays and other resources, and the making and using of the pots. Others might disagree, but my position is that to understand archaeological pottery one begins at the beginning, and for me that beginning resides with an understanding of raw materials and their properties. One then moves on to the complex material and behavioral considerations relating to how the pottery was made, acquired, used, and discarded, and the cultural contexts for all these activities (see Kingery 1996b, 2001). This perspective underlies the organization of both the first and second editions of *Pottery Analysis*.

In the mid-1970s, when I earned my PhD in anthropology, I submitted an abstract for a paper at one of the Society for American Archaeology annual meetings and it was rejected because "there were no symposia on pottery" that it would fit into. Being "object-oriented" back then was not esteemed: although materialism was okay, the material itself wasn't. The focus was on theory and the "new" archaeology. How times change: today, of course, symposia on pottery abound at the SAA meetings and other gatherings of archaeologists and anthropologists.

In the mid-1980s I began writing the first edition of *Pottery Analysis* (hereafter *PA1*). This effort was prompted partly by teaching graduate courses on ceramic analysis, but also by my continuing frustration with communications between archaeologists and first-generation archaeometrists. The former were bedazzled by the latter, who looked upon the former as intellectually challenged bumpkins who just fell off the turnip truck. Archaeometry in those days often provided "clear answers to vague questions" (Rice 1978). That is, answers were provided in parts per billion and with multiple decimal places, but anthropological questions and concepts about ancient human behavior in manufacturing and trading artifacts were not sufficiently refined to take advantage of such sensitivity and precision. The first edition of *PA* was also prompted by my realization that the existing bible for archaeologists (including me), Shepard's *Ceramics for the Archaeologist*, first published in 1956 and reprinted at least eleven times by 1985, was not in tune with the theory and goals of then-current anthropological archaeology.

What was "big" in ceramic analysis preceding *PA1* was the more-or-less-newly emergent role of physicochemical analyses and their uses for studying provenience and trade. These kinds of archaeometric analyses are now fairly routine for archaeologists, with one positive consequence being increased attention to the production and exchange of plain, utilitarian, domestic goods instead of only elite decorated wares. What has emerged as big since *PA1* is the current emphasis on materiality in anthropological theory. Materiality is not solely about the physical object, but rather about the interactions of humans with objects. Humans make and condition objects, but objects also condition humans and, in part, make us social beings. Attention to materiality, plus the prominent contributions of ethnoarcheological studies over the past two decades, has lent a welcome new respectability to the study of pottery and "stuff" in general. One area likely to be big in future technological ceramic studies will be the many new automated, digital, high-resolution, and three-dimensional imagery and tomography techniques.

In writing a book, an author always has to make decisions about point of view and readership. In *PA1*, I tried to stay both fairly general and nonrestrictive in the hopes of making the content as widely useful as possible. Today, with the existence of a vast body of research into ceramics of all stripes, from all parts of the ancient world to modern industry, I am faced with the proverbial abundance of riches. I cannot begin to review and synthesize all these data, or to apply them to all the theoretical, methodological, and topical issues raised by the pottery in all these times and places. So I have had to make choices, and these choices are based on my own experience, which is that of an anthropologically trained archaeologist working in North, Central, and South America.

Thus, this revised edition focuses more on topics and data relating to indigenous cultures of the Western Hemisphere—that is, to post-1985 published studies and examples drawn from research in the Americas and the Caribbean, or work in other areas that has significantly informed Americanists' studies of pottery. I have also tried to incorporate a bit more work on historical archaeology, particularly of the Spanish Americas, as historical archaeology is a fast-growing subfield of archaeology. There is less emphasis on updating discussions of pottery in Europe, Asia, and Africa. This was an uncomfortable decision, as vast amounts of work have been done with pottery in Africa particularly. But my high school–level reading knowledge of French precludes my taking on the formidable body of Francophone literature of Africa or Europe.

Some topics in *PA1* needed updating more than others. Part 1, for example, benefited from a large body of recent literature on pottery origins, and especially on pottery use among mobile or semi-sedentary, nonagricultural groups.

Part 2 treats the raw materials of pottery from chemical, geological, and engineering viewpoints: their occurrence, their properties when mixed with water, and their properties on cooling and heating. The basic geological information about clays was generally well published by the 1960s and I rely heavily on the work of R. E. Grim and

R. W. Grimshaw, as does a recent text on X-ray diffraction of clay minerals: as the authors note, "we ignore the past at our peril . . . we too often discount older works" (Moore and Reynolds 1997: 22). New instrumentation, methods, and publications in ceramic engineering and materials science are largely devoted to what are called advanced ceramic materials, which have little relevance to the study of humble, clay-based archaeological terracottas and earthenwares. In the currently popular idiom of pots having life cycles, these geological resources, in effect, carry the chromosomes—the DNA and proteins and genes—that determine whether the ceramic "organism" has blue or brown eyes and red or brown hair (to pursue the metaphor). The goal of Part 2 is to establish both how these raw materials' properties affect the construction and use of pottery vessels as well as how they shape scientific analysis of the pottery and its interpretation. As compositional and other characterization analyses of archaeological pottery become more and more routine, it is worthwhile to understand how all those trace elements got into the potsherds in the first place.

Part 3 treats the "nurture," as opposed to Part 2's "nature," component of making a pot: the human behavior of forming, finishing, drying, and firing a pot. Chapters follow the procedural sequencing of those in Part 2. I have retained many of the references from *PA1* here because I'm old enough to be tired of watching reinventions of the wheel. I like to believe that the ethnographic observations on pottery making from the mid-twentieth century and earlier may be less contaminated by globalization, plastics, and capitalism than those of the late twentieth century, but this may be wishful thinking at its worst. In any case, that information and its relevance for understanding earlier lives—of people and pots—should not be lost.

Parts 4 and 5 endeavor to update the methods and theories, respectively, that are applied to analyses of ancient pottery to investigate its active use-life. My goal is to introduce these approaches, provide some background development and examples of their use, and offer some cautions concerning their application. Part 5 addresses problems of significant interest to anthropological archaeologists studying ancient pottery, including its production, the kinds and meanings of decorative styles, and the ways pottery containers were used. These chapters integrate much of the empirical, theoretical, and methodological viewpoints of the previous parts. Part 6 concludes with discussion of changes in pottery over time, and the complexities of comparing pottery produced in the age of capitalism and globalization with that of the ancient world.

Parts 4 and 5, more than others, evidence the changes between *PA1* and *PA2*. Revisions of these parts include dividing some of the long chapters in *PA1* into several shorter ones and reordering them. One reason for the differences is that, with archaeometric analyses far more routine in the twenty-first century than in the 1980s, many specialized texts have been published, written by authors with expertise in these methods and their archaeological application. Another reason is that since *PA1* was published in 1987, at least three other general texts on analyzing archaeological pottery have appeared, along with many other more areally focused publications, all providing

varied perspectives. Still another is the ebb and flow, or pendulum swing, of archaeologists' interests. In rewriting *PA2* I have been fascinated by the degree to which certain basic questions and topics have largely stagnated since the 1980s, while others have been pursued with greater enthusiasm and sophistication.

Finally, new theoretical approaches to archaeological pottery have emerged or been strengthened since that time. I try not to take too strong a position pro or con on any of them. However, we are all products of our cultural and enculturational environments, and I acknowledge a preference for the scientific method and the positivism in which I was trained long ago (despite the fact that positivism has apparently "met its demise"; Wylie 2002). Thus the emphasis is more on processual and behavioral approaches, such as ethnoarchaeology, rather than on post-processualist concerns.

Besides the reorganization of the parts and chapters of *PA2*, the text has been substantially rewritten for clarity and emphasis. One major stylistic change in *PA2* is the use of bullet points to highlight important terms or itemizations of the components of some property or concept. Another is the use of boxes, particularly to highlight procedural or methodological steps. These are usually relatively simple techniques that can be pursued in the field or as lab exercises with very little equipment. My hope is that these interruptions of lengthy narrative text will facilitate understanding and reference, given that *PA1* has been used extensively as a textbook and also by archaeologists in countries where English is not the native language. Two topics of *PA1* have been dropped from *PA2*: dating and authentication.

As always, I thank Don Rice for help with new illustrations. I appreciate the assistance of Ann Cordell, Barbara Kerr, and the Clay Mineral Society (Britain) for supplying new figures. Two reviewers of the manuscript provided helpful suggestions and viewpoints, and David Morrow of University of Chicago Press deserves kudos for patience during the long delays in my preparation of these revisions.

Preface to the First Edition

This book is about concepts and issues in the study of pottery. It addresses many aspects of the topic—the nature and properties of the resources of pottery making; the history of pottery; its modern manufacture, use, trade, and discard; and the different perspectives from which it is analyzed. Above all, the book deals with pottery as a source of insights into people and cultures, and it is directed toward those with such interests: primarily to social scientists such as anthropologists, archaeologists, and ethnoarchaeologists, but also to the physical and materials scientists—ceramic engineers, chemists, physicists, and geologists—whose expertise is increasingly being engaged in technical analyses of pottery.

The title was chosen to emphasize the properties and methods of study of *pottery*—that is, relatively low-fired containers made of clay, which have constituted the *batterie de cuisine* of millions of households worldwide throughout the past eight thousand years. The much wider ranges of high-fired, glazed *ceramic* products—including art objects, tableware, structural clay products, plumbing fixtures, and so forth—is intentionally though regretfully slighted. Illustrative material has been selected in light of this emphasis, and examples drawn from historical or modern glazed, high-fired ceramic traditions are relatively infrequent.

This book addresses several objectives. First, it was prepared as a "sourcebook"—it is intended as a relatively broad reference work, but on some levels it must also act as an introduction to the subject. I have thus endeavored to identify and define concepts and terms used in different scientific approaches to pottery analysis, since I believe communication among their practitioners will be promoted by a shared understanding of what such terms mean and how they have come to be used in particular ways.

Second, pottery analysis is undeniably a growing concern. Many national and international symposia are being convened to address various aspects of the topic, and an increasing number of collections of research papers or review articles on pottery analysis are being published. It is more and more difficult to keep up with this expanding literature, and as the field is changing new questions and methods are continually coming to the fore. In consequence, some synthesis—however preliminary—is needed. Much of the current research into past and present pottery traditions addresses complex relations between technical and cultural phenomena—for example, between paste chemical composition and clay resource selection, between vessel shape and functions, and between decorative style and social organization, not to mention investigation of the factors governing assemblage size, determination of original firing temperature, and so forth. Hence this book also attempts to weave the many approaches to pottery—field and laboratory, archaeological and ethnographic, technical and cultural, empirical and theoretical—into a single fabric.

Third, and related to the need for synthesis, the study of archaeological pottery has undergone many recent developments in technical elaboration and precision (in excavation, quantification, coding, compositional analysis, physical and mechanical characterization, etc.). These advances are certainly laudable, but there has not been a commensurate development of theory, or integrated approaches to analyzing and interpreting ceramic data, so that this technical expertise can be optimally utilized. Lacking such theory and integration, researchers may waste time reinventing the wheel, repeating mistakes, and dismissing much of the variability in pottery as insignificant "noise." Because it is such a complex subject, it is easy in pottery analysis (as in other complex areas of research) to oversimplify, reducing complex factors of multivariate correlation and causality to a single attractive or easily comprehended dimension. I hope that efforts to synthesize a variety of approaches to ceramic problems and call attention to the complexity of the issues will not be discouraging but instead will prove challenging and thereby encourage further study.

With these as the objectives of *Pottery Analysis*, I have tried to maintain a balance between depth, spread, and synthesis in identifying focal concepts and issues. I selected some important behavioral questions and research methods in the study of pottery, and for each one—to a greater or lesser extent—I discuss the history of its development, provide an overview of alternative approaches, summarize their advantages and disadvantages, summarize the most recent findings, and confront the problems yet to be satisfactorily resolved. In all these discussions I have endeavored to provide enough basic information to cover the issue adequately, and also to include enough references to pertinent literature so that the interested reader can delve more deeply. Throughout, I have tried to avoid pronouncements on how one should conduct pottery studies, developing instead a broader picture of the ramifications of various procedures or viewpoints. I have also eschewed detailed treatments of archaeological field processing and recording of data, since this is an extremely individualized matter, varying from one field project to another.

Pottery Analysis is organized into three primary divisions treating raw materials, ethnographic and ethnoarchaeological studies, and analytical approaches to pottery, plus a short introduction and concluding section. Each primary division is broadly related to the preceding section(s): for example, the discussion of the properties of raw materials in Part 2 helps lay the foundation for understanding aspects of pottery manufacturing and use (Part 3), and these perspectives in turn establish a basis for identifying research problems and issues for technical analysis (Part 4).

Part 1 (chap. 1) introduces the topic of pottery and ceramics within a historical and geographical framework, summarizing what is known about the origins and history of pottery (and related materials) in different parts of the world. Part 2 treats the raw materials of pottery making, establishing both how their properties affect the construction of pottery vessels and their use and how they shape scientific analysis of the pottery and its interpretation. Within Part 2, chapter 2 discusses clay as a geological

material, the origins of clays, and different kinds of clays; chapter 3 describes the properties of clays when water is added or removed, that is, plasticity and shrinkage; and chapter 4 explains changes in clays fired under different conditions and the composition of glazes.

Part 3 highlights ethnographic and ethnoarchaeological perspectives on various aspects of pottery production and use, with particular attention to the concerns and data base of archaeology. Chapter 5 surveys the technology of manufacture, including clay preparation, shaping, decorating, and firing, and chapter 6 examines the organization of pottery production and distribution. In chapter 7 various approaches to the many functions of pottery are addressed, including clues from vessel form, composition, and direct investigation of the contents. Chapter 8 focuses on decorative style and on the many ways decoration (particularly painting) on pottery has been analyzed and interpreted by archaeologists and ethnoarchaeologists. In chapter 9 some special topics in pottery analysis are investigated: classification, quantification, and use life and assemblage formation.

Part 4 treats characterization of pottery by its physical, mechanical, thermal, mineralogical, and chemical properties. Chapter 10 introduces the background and goals of characterization studies, together with some general questions concerning their design (especially sampling) and interpretation. Chapter 11 is directed toward color characterization—the source and interpretation of differences in pottery colors—and chapter 12 reviews physical, mechanical, and thermal properties, including porosity, hardness, strength and thermal stress resistance. Physiocochemical analysis methods are outlined in chapter 13, which summarizes the general principles, sampling requirements, and information about pottery that are yielded by petrographic analysis, X-ray diffraction, thermal analysis, optical emission spectroscopy, X-ray fluorescence, atomic absorption, neutron activation, electron microscopy, and other methods. Chapter 14 addresses some special research questions to which pottery characterization studies are often directed, such as temper identifications, provenience studies, estimates of firing temperature, and dating and authentication of pottery.

Part 5 (chap. 15) identifies the effects of modern technological developments, colonialism, and tourism on patterns of change and continuity and explores the implications of these findings for archaeological studies of pottery change in prehistory. As cheap utilitarian containers of plastic and metal become widely available, the number of potters making traditional cooking pots and water jars is rapidly dwindling, and with them is disappearing an invaluable source of insights into prehistoric cultures and their artifacts.

A number of people helped me in preparing this book. Among them I would like to thank Wendell Williams and Warren DeBoer, who read various sections of the manuscript, and especially Alan Franklin, who bravely tackled chapters 12–14. Chuck Nelson helped with table 7.1 and Bruce Edwards with Figure 7.9. Don Rice took pictures, switched files, and assisted with matters of design. Parts of this manuscript

were drafted while I held a National Science Foundation Visiting Professorship for Women, and I am grateful for that support.

Note to Instructors

If you have not already done so, please read the Preface to the Second Edition. This new preface explains the goals and point of view of this second edition of *Pottery Analysis* (*PA2*), what I did and didn't do, and the reasons for those decisions, in making this revision. I intentionally did not begin *PA2* by posing key anthropological questions and problems, as we usually admonish our students to approach their archaeological research. Instead, I begin Part 2 with raw materials and their properties, and move to a broad overview of ethnographic data (Part 3) on how potters acquire these resources and manipulate them to create ceramic goods for various purposes. Part 4 covers varied methods, techniques, and related considerations for characterizing the raw resources and finished products of antiquity, with critical attention to what these procedures can and cannot do. Finally, Part 5 addresses some (there are others) of the many meaningful anthropological and archaeological questions and problems relating to pottery, integrating the perspectives presented in parts 2 through 4.

PA2 is, like the first edition of *Pottery Analysis* (*PA1*), intended as a "sourcebook," aiming to be more of a reference work than a course textbook. It is not intended as an introduction to pottery in archaeology: readers are expected to know what sherds are and, ideally, to have already handled a lot of them. Both *PA1* and *PA2* were written out of my experiences of teaching an advanced graduate course in pottery analysis, a course I developed and taught at the University of Florida and then at Southern Illinois University Carbondale. At both institutions the class was intended to explore pottery "from the inside out"—that is, beginning with pottery raw materials and their properties, and moving on to the various ways people manipulated these materials to create useful goods. This provided the foundation for analyzing the various ways pottery functioned, both directly for its actual users and secondarily for today's archaeologists studying it as a medium for understanding past societies.

At both UF and SIUC, class was held in a wet lab equipped with a sink, drying oven, electric kiln, microscopes, and various kinds of glass- and other lab-ware. The course followed the above technological approach on the premise that, to understand archaeological pottery and its uses, students should begin with a hands-on understanding of raw materials. Students were asked to collect clays from near sites they were working on, or they were assigned a clay from material I had accumulated. They brought these materials into the lab, and then over the early part of the semester they carried out the simple exercises I describe in boxes in the text. They added different amounts of water and different kinds and sizes of tempering material; they formed test bars and dried, fired, weighed, and measured them to learn about sticky clays and lean clays and shrinkage and warping and color development. The value of this practical approach was brought home to me each time I explained the postfiring problems caused by calcite/limestone temper (see sec. 6.2.4): the students met my explanation with ill-

concealed skepticism until they came back to their calcite-tempered bars a week after firing . . . and found them in crumbs. This hands-on, starting-with-local-clay approach is also useful for ceramic analysis instruction in conjunction with a field school.

Of course, not all instructors of courses in pottery analysis may want to begin this way. They may lack the wet-lab set-up, they may be less concerned with technology, they may want to begin by investigating a specific collection of potsherds and a culture-historical problem, they may want to run the class primarily as a readings class or use a theory-driven, case-study approach, or something else entirely. In such cases, the instructor might prefer to begin reading assignments somewhere in the later, more archaeological parts of *PA2*, rather than with Part 2. Similarly, an instructor might wish to advance his or her own particular theoretical position for exploring archaeological or ethnographic pottery. For this reason I do not begin *PA2* by introducing my own theoretical perspectives on interpreting archaeological materials. Instead I provide an overview of some of these approaches in chapter 12.

PA2, then, is a sourcebook. It is intended to lead readers into the literature and to serve as a reference. Chapters may be assigned in or out of sequence, beginning anywhere in the book as it suits the instructor's preference. For reasons of length and cost, it was impossible to include in this single volume all the multitude of viewpoints and topics relating to pottery analysis that make it an exciting and challenging field of study. Thus users of this volume will likely want to assign additional readings to supplement the topics discussed (or omitted) in *PA2*.

Part 1

Introduction

> Instead of thinking of our pile of artifacts as our prison, we should consider it a key to unlocking a humanity that only we can access.
>
> **Skibo 2009: 40**

The history of manufacture and use of pottery encompasses roughly twenty thousand years. Worldwide, pottery began to be made and used in many different times and places, likely as practical containers in some and as prestige or ritual items in others. Throughout this history, ceramic products have been studied from varied points of view, including artistic, aesthetic, archaeological, historical, classificatory, mechanical, mineralogical, and chemical. Appreciation of the aesthetic qualities of early Chinese porcelains stimulated Islamic potters to try to reproduce them in the ninth century. The antiquarianism of the Renaissance and post-Renaissance centuries fostered interest in collecting Greek and Roman vases and an awareness of early civilizations and their achievements. Mineralogical and chemical experiments by early modern European potters and scientists trying to imitate Chinese porcelains led to improvements in their own manufactures, such as bone china.

Modern archaeological investigations have generally devoted considerable attention to ceramics in their reports, and this is true for myriad reasons. An obvious one is pottery's long history and recovery in virtually all parts of the world, its presence rarely limited by geological or environmental situations or conditions of preservation. Pottery is essentially nonperishable as a function of its physical properties: although a pot may break, its fragments may survive for millennia. Potsherds are not particularly appealing to looters of archaeological sites, unlike chipped stone projectile points, and thus are less likely to be selectively removed; unfortunately, however, the same cannot be said of intact vessels found in tombs or other special contexts.

Finally, pottery is formed and *in*formed: pottery making is an additive process in which the successive steps are recorded in the final product. The shape, decoration, composition, and manufacturing methods of pottery, when considered in light of contexts of recovery, reveal insights into its uses and hence into human behavior and the history of civilizations. Potters' decisions about raw materials, shapes to be constructed, and kinds and locations of ornamentation all stand revealed, as do cooking methods, refuse

disposal patterns, and occasional evidence of clumsiness and errors in judgment. The sensitivity, spatial as well as temporal, of pottery to changes in such culturally conditioned decisions has fed archaeologists' traditional dependency on this material for defining prehistoric cultures and their interrelations.

Archaeologists' and anthropologists' attention has increasingly turned to pottery manufacture and use among groups being rapidly incorporated into the global economy. In both hemispheres the traditional craft of the potter, often a household livelihood passed down from generation to generation within a family, is suffering at the hands of modernization and industrial capitalism. Plastic and metal utensils are relentlessly usurping the utilitarian functions of jars and bowls formerly made of clay, because these new materials result in cheaper, more durable products. Although traditional peoples everywhere likely believed that water is more refreshing when cooled in a porous terracotta jar or beans are more flavorful when cooked in an earthenware pot, indulging these preferences is more and more difficult as potters abandon their profession to "progress" and the global economy.

Modern ceramic industries, sensitive to the needs of a technologically oriented society, now produce ovenware, flameware, and freezer-to-stovetop cooking utensils, plumbing fixtures, refractory brick for steel furnaces, dentures, and containers for radioactive waste. Meanwhile, the dwindling numbers of traditional potters turn to producing flowerpots, ashtrays, and figurines for a tourist market that too often has little appreciation for the dignity and history of their art. Fortunately, the value of studying contemporary potters and their products has not gone unrecognized, as an aid to archaeological interpretation of the distant past, as a key technology in human interactions with their environment, and as a means for many peoples to recover part of their heritage before it is irrevocably lost.

1 Pottery and Its History

> There is in pottery a thread of connection with the earliest traditions of civilization and culture. Pottery forms, even simple ones like cups or plates, still symbolize for us in a particularly direct way some of the most fundamental of human activities.
>
> Rhodes 1973: xviii

Pottery and ceramics can be conceptualized as artificial stone, the first synthetic material created by humans thousands of years ago. Familiar kinds of ceramics include containers and art objects of terracotta, earthenware, stoneware, and porcelain. Less obviously, perhaps, ceramics also encompass bricks, roof and floor tiles, sewer pipe, glass, and vitreous plumbing fixtures, as well as cements and plasters, abrasives, refractories, dentures, enameled metals, insulation and conduction parts, braking devices, space-shuttle tiles, and electronics. Surgeons now routinely make use of bioceramics: materials that can bond to living human tissue and are useful for implants and prostheses (Hench 2013). Out of early mixtures of earth, water, fire, and air, pottery transformed a range of human endeavors, from ancient cuisine to modern medicine and space exploration.

1.1 Pottery and Ceramics: Definitions and Products

The term ceramic comes from *keramikós*, a reference to Kéramos, mortal son of Greek gods Dionysos and Ariadne. Kéramos was lord of the potters' district (Kerameikos) outside the main gate of Athens, which was the site of an ancient cemetery and location of excellent potters' clay (*kéramos*) used to make the famous Attic vases of Greece (Harrison 2012: 22–23; http://www.theoi.com/Olympios/DionysosFamily.html#Attika; http://odysseus.culture.gr/h/3/eh351.jsp?obj_id=2392). Although in popular usage ceramics denotes things made of fired clay, the word has two sets of overlapping meanings, one set common to materials science and another employed in art and archaeology, which complicate its precise definition and usage.

In modern materials science and industry, ceramics is a generic term for an inorganic crystalline compound combining a metal with a nonmetal. Historically, most ceramics are clay-based materials composed primarily of alumina (Al_2O_3) and silica (SiO_2). Today's advanced ceramics, however, may be compounds based on oxides of magnesium, calcium, titanium, iron, zirconium, and other elements in the absence of clay. These materials have extreme mechanical and thermal properties allowing them to serve in aerospace, nuclear, and electronics industries (see, e.g., Aldinger and Weberruss 2010). Thus ceramics may refer either to the entire range of compounds of metals and nonmetals or slightly more restrictively to materials—including noncrystalline glasses—manufactured from silicates and hardened by applying heat. In these usages, the term also encompasses the research and applied fields developed around these materials, that is, ceramic science, ceramic engineering, and ceramic industry, which are concerned with the manufacture of structural, refractory, electronic, and glass products. Pottery, one of the industries within the overall ceramic field (table 1.1), is primarily devoted to low- and high-fired tableware and utensils.

Table 1.1 Principal Ceramic Industries

Industry	Product
Structural ceramics	Bricks, tiles, drainpipes, concrete
Pottery	Terracotta
	Earthenware, glazed and unglazed
	Stoneware
	"China" tableware
	Porcelain
Refractories	Fireclay bricks, crucibles
Glass	Glasses, glazes
Advanced ceramics	Electronics, refractories, biomedical devices, abrasives, semi- and superconductors, insulators

In art and archaeology the term ceramics usually excludes construction or industrial products and conforms more closely to dictionary definitions, which emphasize clay working and the plastic arts. Within these fields, ceramics generally refers to cooking and serving utensils and objets d'art manufactured of clay. Even here the term is sometimes employed more specifically to distinguish high-fired, usually glazed, and vitrified ceramics from pottery: low-fired, unvitrified objects and/or cooking and storage vessels. In Asian studies an even finer distinction may be made, whereby ceramics denotes glazed and vitrified material (such as stoneware) intermediate technologically between low-fired pottery and high-fired translucent porcelain.

In terms of these several criteria of function, firing, and composition, archaeologists and anthropologists investigating clay-based goods produced by traditional or nonindustrial methods treat only a subset of the diverse field of ceramics. A rigid distinction between ceramics and pottery is often difficult to maintain, but, given the broad range of meanings, the bulk of material treated by anthropologists and archaeologists is generally more properly referred to as pottery.

Table 1.2 Ceramic Bodies and Their Characteristics

Body Type	Porosity	Firing Range	Typical Applications	Comment
Terracotta	High: 30% or more	Well below 1000°C	Flowerpots, roof tiles, bricks, most archaeological pottery	Unglazed, coarse, and porous; often red-firing
Earthenware	Usually 10–25%	Wide: 900–1200°C	Coarse: drainpipes, filters, tiles, bricks	Glazed or unglazed; body nonvitrified
			Fine: wall and floor tiles, majolicas	
Stoneware	0.5–2.0%	ca. 1200–1350°C	Glazed drainpipes, roof tiles, tableware, artware	Glazed or unglazed; vitrified body
"China"	Low: usually less than 1%	1100–1200°C	Tableware	White, vitrified
Porcelain	Less than 1%; often nearly 0%	1300–1450°C	Fine tableware; artware; dental, electrical, and chemical equipment	Hard body; fine, white, translucent

Ancient and modern pottery and ceramics are grouped into various categories called wares or bodies (table 1.2) on the basis of their composition, firing, and surface treatment (Hopper 2009: 36–39). The broadest division distinguishes unvitrified from vitrified wares depending on whether the composition and firing are such that the clay melts and fuses into a glassy (i.e., vitreous or vitrified) substance. Low-fired, unvitrified pottery includes terracottas and earthenwares; high-fired, vitrified ceramics include stonewares and porcelains.

Terracotta (It. "cooked earth") is a relatively coarse, porous ware fired at low temperatures, usually 900°C or less. The earliest fired pottery in all areas of the world falls into this category. Terracotta vessels, figurines, sculptures, and tiles are generally not covered with a glaze, but they may exhibit various surface treatments that enhance their function and aesthetic appeal. Terracottas are often subsumed within the broader category of earthenwares.

Earthenwares also include porous, unvitrified clay bodies, but they are fired at a wide spectrum of temperatures from 800/900°C or so up to 1100/1200°C. Earthenwares may be glazed or unglazed; although the body itself is not vitrified, the firing temperature can be high enough to allow a glaze to form properly. This category of ceramic material includes a wide range of products, from coarse red earthenwares such as bricks and tiles (sometimes called heavy clay products) to fine earthenwares such as tin-enameled majolica, often made with more refined clay bodies. Earthenwares have

served an enormous variety of household and construction purposes throughout the world for many millennia.

Stonewares are fired at temperatures of roughly 1200–1350°C, high enough to achieve at least partial fusion or vitrification of the clay body, depending on its composition. The medium-coarse body, opaque and usually gray or light brown in color, is composed of stoneware clays, typically highly plastic sedimentary deposits low in iron. Stonewares may be unglazed or have a lead or salt glaze.

The pinnacle of the potter's art, at least in terms of technical accomplishments, was reached with the Chinese production of porcelain, a thin-walled, translucent, vitrified ceramic customarily fired at temperatures of 1280–1400°C or higher. Porcelains are made of a white-firing, highly refractory kaolin clay (sometimes called china clay), relatively free of impurities, mixed with quartz and feldspar. During high-temperature firing the feldspar melts, giving the finished product its characteristic translucency, hardness, and melodious ring when tapped.

1.2 The Earliest Pottery

It is impossible to trace precisely the beginnings of human exploitation of the world's resources of clayey substances. Although early stone tools from Africa are more than a million years old, the oldest objects of clay that archaeologists have recovered date only in the tens of thousands of years. However, humans likely experimented with soft earthy materials considerably before this, perhaps hundreds of thousands of years ago, in uses as ephemeral as painting their bodies with ochre (see Wreschner 1985). Clay might have been eaten, a not-uncommon practice known as geophagy or pica, claimed to add nutrients and remove toxins (e.g., Knishinsky 1998; Young 2012), the latter a form of self-medication. But the essential feature in the history of clay technology is the application of heat to transform this soft, malleable material into something hard and durable. A relatively recent achievement by the yardstick of prehistory, it is this transformation that allows broken bits of pottery to survive millennia and come into archaeologists' hands for study.

Any discussion of the history of pottery and ceramics must begin with the recognition of clay itself as a useful resource (table 1.3). Clay is certainly one of the most abundant, cheap, and adaptable raw materials available for human exploitation. Early archaeological evidence for its use includes slabs found near a hearth in a Middle Paleolithic cave in Monaco, perhaps used for grilling meat (Hayden 2010: 19), and the lining of a hearth 34,000–32,000 years ago in Greece (Karkanas et al. 2004). More common findings appear as part of the diverse artistic expressions of the Upper Paleolithic period of central and western Europe. Many Paleolithic caves have designs traced into wet clay on walls and floors, in addition to the more familiar animal paintings. At the Tuc d'Audoubert cave in France two modeled bison were found, formed of unfired clay. The famous "Venuses"—female figurines with exaggerated sexual characteristics—include specimens formed of fired and unfired clay from Dolní Vestoniçi in Czechoslovakia; dating around 25,000–30,000 years ago, some were made of clay mixed with crushed mammoth bone (Vandiver et al. 1989). Other Late Paleolithic central Eurasian sites have yielded thousands of "anthropomorphic figurines, zoomorphic statuettes, pellets, 'earplugs', flat fragments and 'structural ceramic'" (Budja 2010: 507).

Table 1.3 Chronological Sequence of Developments in Pottery and Ceramic Technology

Development	Europe	Near East	Far East	Western Hemisphere
Fired clay figurines	Dolní Věstonice, 25,000 bc		Japan, pre-10,000 bp	Mexico, 2300 bc
Pottery containers		Zagros, 10,000 cal. BP	China, 18,000 bc	Brazil, 5671 cal. BC
Kiln		Iran, 7th mill. bc	China, 4800–4200 bc	Mexico, 1000 cal. BC
Wheel		3500 bc	China, 2600–1700 bc	[16th century AD]
Brick—adobe		Zagros, 7500–6300 bc		Coastal Peru, 1800 bc; Mexico, 900–800 bc
Brick—fired		Sumer, 1500 bc		Mexico, AD 600–900
Stoneware	Germany, 14th c. AD		China, 1400–1200 bc	
Glazes				
Hard		16th c. bc	China, 1028–927 BC	
Lead		100 bc	China, 206 BC–AD 221	
Fritted			China, 8th c. AD	
Tin	Spain, 10th c. AD	Assyria, 900 bc		
	England, 17th c.			
Salt	Germany, 16th c.			
Porcelain	Germany 1709		China, 9–10th c. AD	
	France 1768		Japan, 1616	
Bone china	England, late 18th c.			
Gypsum plaster mold	Italy, 1500			
Jiggering	1700			
Slip casting	1740			
Pyrometric cones	1886			

Note: Unless otherwise indicated, early dates given here are uncalibrated bc. Early dates in the Americas are from Clark and Gosser 1995: table 17.1. See text note 1 and text for other sources.

These examples suggest that by 25,000 years ago, three significant principles of clay use were already widely known. One is that moist clay is plastic: it can be shaped and formed and will retain that form when dried. Another principle is that fire hardens clay. A third is that adding various substances to clay can improve its properties and usefulness. The application of these principles to create durable containers was a significant technological innovation.

1.2.1 Pottery Containers: Why Pots?

The appearance of pottery vessels in the archaeological record has long been considered a major marker in human "progress." In nineteenth-century evolutionary schemes, pottery was interpreted as marking the movement of human societies from "Upper Savagery" into "Lower Barbarism" (Morgan 1877). Later, pottery was seen as part of the "Neolithic technocomplex": an assemblage of tools for obtaining, preparing, and storing food, plus the associated technologies of their manufacture and use, that accompanied changes in lifeways during the Pleistocene/Holocene transition. These changes included the adoption of food production rather than collecting, along with settlement in permanent villages instead of temporary encampments. In contemporary thinking these transformations have been decoupled and each is seen as highly complex, occurring over several millennia and at different times and in different ways in different areas.

Indeed, the origins of pottery—the beginnings of the use of clay to make fired containers—are far more complicated than they would seem. For archaeologists, the interesting questions are not solely about the when and where but also the why and how: How was it learned that clay could be shaped into hollow containers? Was the early pottery in a given site or area an independent invention or inspired by another group? How was it discovered that fire-hardened clay had both utilitarian uses and social functions? Did these processes co-occur or were they independent? A particularly interesting question concerns whether early pottery containers represent a "practical" or a "prestige" technology (Hayden 1998).

Unfortunately, simple answers to these kinds of how and why questions in archaeology are not easy to come by. Multiple rather than single causes are more probable explanations for almost all early cultural developments; thus the beginnings of pottery may be a consequence of numerous lines of experimentation and accumulation of practical experience. Issues relating to the innovation and innovators of this new technology, along with its sharing, copying, adoption, and dispersal, intermingle varying combinations of both similar or general and dissimilar/specific (localized) circumstances.

1.2.1.1 Hunting-Gathering-Foraging-Collecting

Accumulating evidence for the presence of pottery among non-sedentary peoples is of particular interest (table 1.4). Considerable research during the past few decades has shed light on early clay use and pottery origins as well as the earliest expressions of emerging societal complexity (see e.g., D. Arnold 1985: 119–20; J. Arnold 1996; Barnett and Hoopes 1995; Eerkens et al. 2002; Freestone and Gaimster 1997; Jordan and Zvelebil 2010a; Mack 1990; Saunders and Hays 2004). Pottery does not seem to have originated in any single time and place in human history. Rather, it is evident that, after the close of the Last Glacial Maximum, about 20,000 years ago (Clark et al. 2009), pottery began to be independently invented in a thus-far unknown number of centers in both hemispheres among non-sedentary, nonagricultural groups.

Table 1.4 Relation between Pottery Making and Sedentism among Fifty-Nine Ethnographic Societies

	Settlement Type			
	Non-sedentary	Partially Sedentary	Fully Sedentary	Total
Pottery-making societies	2	12	32	46
Non–pottery-making societies	6	4	3	13
Total	8	16	35	59

Source: Arnold 1985: table 5.3. From the Human Relations Area Files Probability Sample Files.

The "back story" in this process involves considerable rethinking of the nature of hunter-gatherer societies, particularly those at the close of the Pleistocene and during the Pleistocene/Holocene transition. Various studies have discussed subsistence and settlement strategies, with some agreement that "hunting and gathering" (including fishing) can be differentiated into foraging and collecting systems (Binford 1980). Foragers are characterized by broad-spectrum resource use and relatively high mobility (Bettinger 2010; Kelly 2013); collectors focus on a more limited range of items and exhibit relatively lower mobility. The nature of residential mobility itself is being rethought (Kelly 1992), with distinctions framed in terms of seasonal patterns of settlement or circulating versus radiating settlement (Lieberman 1993) on the basis of the longer and larger semi-sedentary residence in base camp/macroband settlements. Such extended occupations are found in areas with greater seasonal availability of highly productive foodstuffs, and are associated with the intensification of resource use. Finally, subsistence variability among these groups may be differentiated into time-minimizing and energy-maximizing (Bettinger 2001) and storing versus nonstoring economies (Testart 1982; see also Ingold 1983), and as delayed-return versus immediate-return consumption patterns (Dale et al. 2004; Woodburn 1982).

In other words, hunting-gathering-fishing-foraging-collecting systems are now understood to be more complex than originally conceived. Some settlements display archaeological signatures of sedentarization, loss of egalitarianism and emergence of social ranking, and increasing societal complexity, for which reasons the residents are labeled complex, affluent, and/or transegalitarian hunter-gatherer-collectors. And in terms of material culture, it is among these groups that very early pottery was frequently manufactured and used. Several general scenarios can be proposed to explain this development.

1.2.1.2 Hypotheses and Models

One explanation calls attention to the need for storage of food surpluses resulting from intensification of certain resources in storing or delayed-return economies. Storing economies tend to be more common in areas of strong seasonality in resource availability (relating to both kinds and amounts, and to problems of spoilage). Hence they are generally rare at low latitudes (below c. 28° N latitude) and in deserts and tropics, and more common at higher latitudes and in temperate climes (Rice 1999: 34–35). If pottery containers began among complex, storing hunter-gatherers with the need for safe, rodent-proof, long-term storage facilities for surpluses—or for caching foodstuff at various locations in their movements across a landscape (Ingold 1983)—this suggests that early pottery was a "practical" technology (see Hayden 1998: 17).

The most common and traditional explanation for pottery containers is a "culinary hypothesis," in which pottery manufacture and use are entangled with the domestication of grains and animals and establishment of sedentary village life as part of a "Neolithic Revolution" (Childe 1936: 93–94; cf. Vitelli 1989). Although this specific correlation can no longer be supported, it is likely that pottery originated as—and has continued to be—part of women's work in the kitchen (see Crown and Wills 1995: 245–48; Rice 1991b; Skibo and Schiffer 1995; Wright 1991; also Vincentelli 2004). Clay-lined fire pits, for example, would call attention to the durability and impermeability of the burned clay and the advantages of portable containers (see Karkanas et al. 2004). Sun-dried clay slabs could have held dry goods such as grains, seeds, or nuts for toasting. Clay might have been used to line baskets (e.g., Wormington and Neal 1951) and then, after the basket was set too close to a fire and burned, the hardened lining was found to be useful itself. In many parts of the world the earliest pottery vessels known archaeologically are skeuomorphs, in forms or with decoration resembling containers of perishable basketry, netting, gourds, wood, animal skin, and so on (Joesink-Mandeville 1973; Speck 1931; see also Doumani and Franchetti 2012; Russell 1991). Women were likely intimately familiar with these technologies.

Another set of propositions about pottery origins (also appropriate for its adoption) focuses on the role of an accumulator or aggrandizer—an enterprising individual or a kin group seeking to build power and prestige (Hayden 1998: 18–25). This "aggrandizer/feasting hypothesis," which might be considered a theoretically more robust variant of the culinary hypothesis, is set against the background of subsistence intensification among semi-sedentary, transegalitarian hunter-gatherer groups in the late Pleistocene/early Holocene. As these groups intensively exploited certain highly productive resources, the aggrandizing agent accumulated prestige by staging large feasts featuring rare and desirable foods (Hayden 1990, 1995; also Brown 1989). Such foods might include various kinds of oils and fats as well as fermented beverages (Hayden 2010: 22–23; Rice 1999: 33–34). Displays of innovative and aesthetically pleasing containers for serving these foods, such as stone bowls and pottery, would have enhanced the impressiveness of the event, underscoring assertions of power, identity, and prestige of the host, and thus early pottery would have been a prestige

technology (Hayden 1995, 1998: 28–30; see also Harry and Frink 2009; Olausson 2008). Further generosity, such as giving pots (or other prestige goods) to the attendees at these feasts, which is common on such occasions, would have led to further accrual of social capital and might have cemented potential alliances in power negotiations (e.g., Wallis 2011).

Several variants of this popular hypothesis exist. One is an estuarine hypothesis (Goodyear 1988: 321; Jordan and Zvelebil 2010b: 58–61), better termed a "littoral-riparian hypothesis." Given the advantages of fired clay containers for boiling to extract nutrients from shellfish and other aquatic resources in high-energy coastal environments such as estuaries (Yesner 1980), pottery might have been developed in these areas as part of seasonal semi-sedentary encampments. Most of the examples of early pottery dispersal in northern Eurasia come from aquatic environments (Jordan and Zvelebil 2010a), including lakes and the mouths of rivers, as do those in the Southeastern United States (Sassaman 1993; Saunders and Hays 2004; see also Erlandson 2001 for early aquatic adaptations; Zangrando 2009 for the implications of fishing intensification). The cooler temperatures of northern climates would have meant slower and safer drying of vessels formed from the fine, sedimentary clays in these coastal-estuarine areas. In addition, these clays are likely to contain significant loads of salts (e.g., chlorides) and organics that, on drying, typically form a surface coating that might have increased the hardness or strength of unfired or low-fired vessels. Or, containers might have been coated with organic materials such as seal oil and blood, as with Arctic North American unfired pottery today, to harden the surface to make it watertight (Harry et al. 2009). Unfortunately, most of the earliest coastal and river-delta sites the world over were likely inundated by postglacial sea rise and forever lost to archaeology, although once sea levels stabilized similar productive environments and related biotic zones would have redeveloped along the new coastlines and river mouths. In these areas—coastal estuaries, lakes, streams—fine, organic, highly plastic clay sediments are readily accessible.

Several alternative interpretations of the aggrandizer model exist. One suggests that pottery would more likely be developed in areas of resource scarcity rather than abundance (Oyuelo-Caycedo 1995: 134). Another suggests that collective rather than individual agency may instead operate (Pearson 2005). Yet another addresses decoration, proposing that such elaboration would be significant in situations of increasing sedentarization to assert social identities and/or territorial boundaries (Kelly 1991: 145–46; Mizoguchi 2003). Increasing attention is given to pottery manufacture and use among residentially mobile peoples, such as pastoralists, and their exchange relations with sedentary agriculturalists (Beck 2009; Doumani and Frachetti 2012; Eerkens 2003, 2008). Analyses of carbonized residues on pottery dated to the period of transition to agriculture around the western Baltic Sea (northern Europe) recovered lipid biomarkers revealing continued use of marine resources along with the presence of domestic animals (Craig et al. 2011).

Yet another explanation of pottery origins is an "architectural hypothesis," linking the creation of fiber-tempered pottery to making structures of adobe (mixtures of clay and straw) and to the firing technology of early plaster. Pottery in the Near East may have developed out of early "software" technology (Vandiver 1987: 10, 29, citing Dyson 1965), in which earthy materials were used to make plasters, pigments, bricks, sling balls, and so on. Firing these materials was a later, independent development.

1.2.2 Software

The concept of a software stage or phase in ceramic technoscience is a useful one and appears to be supported in several parts of the world. In these areas—primarily temperate climates and/or high latitudes—unfired and low-fired clay containers have been recovered in sites associated with intensifying subsistence/settlement strategies occupied by transegalitarian, seasonally semi-sedentary collectors during the late Pleistocene or early Holocene eras (late Paleolithic, Mesolithic, and early Neolithic in Eurasia and Africa; Paleo-Indian and Archaic in the Western Hemisphere).

An early software phase may be represented by objects such as the Dolní Věstonice figures and parietal art in Late Paleolithic Europe, items constituting a very early prestige technology. It is among such groups, often seen to be "enmeshed in relationships of unequal power" when viewed in broader context (Morrison 2006: 281), that the accumulator/feasting hypothesis is most robust. Competitive feasts were likely among the strategies deployed as part of the social integrative rituals common to seasonally expanded, semi-sedentary settings.

The main software phase is generally later and more widely evident, for example by unfired or very low-fired ("subceramic") fiber-tempered clay containers recovered from transitional Pleistocene/Holocene sites. Modifying a clay with absorbent plant fibers or other organic matter may have helped the clay dry more quickly compared with mineral tempers (Skibo et al. 1989). This technology was practiced by nonagricultural and mobile or semi-sedentary peoples in the Late Pleistocene, and it is also practiced by non–food-producers in modern times (e.g., Ochsenschlager 1974). In addition, various organic coatings might have enhanced the durability of software containers, as with the seal oil and blood used by Arctic North American potters as a glue and to harden the surface and reduce permeability (Harry et al. 2009).

Such unfired and low-fired clay objects are ephemeral, easily broken or crushed in use, dissolved by liquid and quickly returning to their original state, or fragmented by freeze-thaw cycles in temperate and colder environments or heating-cooling cycles during cooking. In addition, the ancient use and modern archaeological recovery of unfired clay objects—possible prototypes for fired ones—are partially dependent upon the dried clays' durability or resistance to mechanical stresses in handling and use. These objects leave only rare traces in the archaeological record, primarily in arid areas or tombs, or in caves where needs and uses might have been a restricted subset of

a larger range. Thus the earliest uses of clay for making containers remain poorly documented.

In sum, pottery, rather than being a sudden transformative invention of the Neolithic Revolution accompanying early agriculture, is better considered in terms of an already familiar raw material (clay) and its technical manipulation—forming container shapes and baking them in the sun or a fire. The appearance and widespread adoption of fired pottery reflects continuing and new practical needs for tools and resources, which relate to preparing and/or storing increasingly important foodstuffs such as shellfish in coastal areas, especially at high latitudes, and wild, cultivated, and eventually domesticated seeds, grains, and tubers among semi-sedentary peoples in varied regions. The early use of pottery must be understood in light of related food-getting and -processing technologies, such as ground stone, but this is beyond the scope of the present chapter.

1.3 Pottery and Ceramics in the Old World

1.3.1 Eastern Asia

The earliest innovations in virtually all stages of the potter's art—including the earliest fired pottery—occurred in the northern Far East, primarily in China and Japan. In addition, sites in the general area of the Amur River valley in China, eastern Siberia, and Korea have yielded pottery dating well before 10,000 years ago[1] (Derevianko et al. 2004; Kaner 2003; Kuzmin 2006; Kuzmin et al. 1997; Zhushchikhovskaya 1997). A critical factor behind these early dates may be that this region remained unglaciated during the Last Glacial Maximum (Clark et al. 2009).

Caves in southeastern China yielded pottery from sediments with calibrated radiocarbon dates of 15,000–20,000 years ago. At Yuchanyan Cave in Hunan Province, clusters of pottery fragments represented two pots. One reconstructible vessel was thick-walled, with a rim diameter of 31 cm, a pointed base (a form known as a *fu*), and cord-impressed interior and exterior; the coarse kaolinite-based paste was fired to ~400–500°C (Boaretto et al. 2009). Even earlier, pottery unearthed in recent excavations at Xianrendong Cave in Jiangxi Province was dated around 20,000 years ago and was likely used for cooking (Wu et al. 2012).

Pottery of the Jomon culture in Japan was once thought to be the earliest in the world. The Jomon culture flourished from about 14,500 BC and its expressions are differentiated into six phases, with eastern and western distinctions (Habu 2004). Overall, the culture is described as one of complex or affluent hunter-gatherer-collectors living in semi- or seasonally sedentary villages, with food storage pits, specialized subsistence strategies that included plants and marine foods, and long-distance trade, but lacking agriculture (Underhill and Habu 2006: 134–42).

The earliest Jomon pottery is represented by 46 plain fragments from the Odai Yamamoto I site in extreme northern Honshu. Five radiocarbon dates were obtained from carbonized material on the surfaces and ranged around 13,780 ± 170 bp, or cal. (1**σ**) 14,900–14,250 BC (Underhill and Habu 2006: 136, 143n2; Habu [2004: 29] gives 13,800–12,700 bp, or 16,500–14,900 cal. BP; see also Kaner 2003). Incipient Jomon pottery occurs primarily as small, deep pots, often fiber-tempered, thin walled, and formed by slab construction; later pottery is coiled (Harris 1997: 23–24). "Jomon" means cord-marked, one of the ware's characteristic surface treatments.

Although the entire range of early through late Jomon pottery is characterized by impressed and modeled/appliqué decoration, the most elaborate of these products were produced in the Middle Jomon period (~3700–2600 cal. BC). Vessels feature appliquéd fillets and buttons and deeply incised grooves on their narrow bodies and especially on their large, elaborately castellated rims (fig. 1.1). They appear top-heavy, unstable, and poorly suited to practical use. Middle Jomon sites also yield so-called ritual artifacts

including figurines, clay masks, jade beads, stone rods and "swords," and other items (Habu 2004: 142–59).

In China little is known about the development of the potter's art after its earliest beginnings. Pottery from coastal southeast China and adjacent regions consists of a variety of cord- and shell-marked and incised types, with dates ranging to about 10,000 years ago (Chang 1977: 85–90; Wang and Zhou 1983: tables 1 and 3). Between 4800 and 4200 BC potters at Banpo and other Yangshao (Neolithic) villages produced beautiful hand-formed jars and dishes painted with red-and-black geometric decoration (fig. 1.2). These wares were fired on the outskirts of the villages in small, subterranean horizontal and vertical updraft kilns (fig. 1.3), which could achieve firing temperatures of 950°C (Li Jiazhi 1985: 143; Shangraw 1977). Incising on some of the Banpo vessels has been interpreted as maker's marks associated with particular family lines (Chang 1983: 84–86) and may show some relation to later characters, particularly numerals, in Chinese writing (Cheung 1983).

Figure 1.1 A late Jomon jar from Japan, showing characteristic cord marking; height 47 cm. Courtesy Royal Ontario Museum, Toronto, Canada.

There is little evidence for the beginning of use of the potter's wheel in China. It has been suggested that a low, thick-walled, dish-like vessel commonly found at Yangshao sites between 4800 and 3600 BC may actually have been used as a tournette, a slow or low-speed wheel (Zhou Zhen-xi 1985). The fast or true wheel was apparently used during the Zhou (Chou) period, roughly the first millennium BC (Hobson 1976: 2).

Chinese ceramic history is marked by numerous technical achievements of lasting impact, particularly in high-fired bodies and glazes (Li Jiazhi 1985; Zhang Fukang 1985). By the Middle Shang period, between the fifteenth and thirteenth centuries BC, stonewares were being produced in kilns capable of reaching 1200°C (Li Jiazhi 1985: 144). At about the same time, glazes were produced using a combination of CaO (lime) and wood ash as fluxes (Zhang Fukang 1985: 164, 170), so vessels may have been given a "natural kiln glost" from wood ash during the firing. True hard (feldspathic)

glazes began to be used a few centuries later in the Early Western Zhou period (Shangraw 1977: 383, 1978: 43–46).

Figure 1.2 A late Yangshao funerary urn of Banshan type, from northwest China. After Blandino 1984: 15.

One of the most spectacular finds of archaeological pottery in China is the army of 7,500 life-size soldiers and horses found in 1974 near Xian. Guarding the massive mausoleum of Emperor Qin Shi Huang, the first unifier of China in 221 BC, the individuals in the terracotta army were formed in separate pieces but without molds (Hearn 1979: 46–48; Museum of Qin Shi Huang 1981: 11–14). Solid or hollow legs support hollow torsos made of coils of clay; heads, arms, and legs were shaped separately, then attached to the bodies with strips of clay. Individualized facial features and costume details were sculpted or appliquéd to finish the pieces before firing, then after firing the figures were painted with red, green, black, and other colors.

The most enduring legacy of Chinese potters is porcelain, called *porcellana* (shell) by Marco Polo, the late thirteenth-century explorer, because of its delicate translucency. The origins of porcelain are uncertain and historical texts are inconclusive: there is no single Chinese word for porcelain as distinct from other kinds of pottery, although the

beginning of a new written character, *tz'u* (or *ts'e*) during the Han dynasty (206 BC to AD 220) has sometimes been interpreted as signaling the creation of a distinctive new ceramic product (Hobson 1976: 140–42). Various early high-fired white wares lacking true porcelain's characteristic translucency have sometimes been called proto-porcelains or "porcellanous" stonewares and are known from the Han dynasty and particularly the T'ang dynasty, AD 618–906 (Hobson 1976: 148). White, hard, and resonant, porcelain reached its finest development in the Song dynasty (AD 960–1279) and thereafter.

Chinese porcelains are most closely identified with the "imperial kilns" at Jingdezhen (Hu and Li 1997). This city rose from a humble riverside market town in northern Jiangxi (Kiangsi) Province to become "the metropolis of the ceramic world, whose venerable and glorious traditions outshine Meissen and Sèvres and all the little lights of Europe, and leave them eclipsed and obscure" (Hobson 1976: 152; Tichane 1983). Although skilled potters were to be found in the area centuries earlier, the meteoric rise of Jingdezhen as one of the world's great ceramic centers began when Emperor Ching Te (AD 1004–1007) of the Song dynasty decreed that its kilns should produce wares for the imperial capital (Hobson 1976: 45, 156).

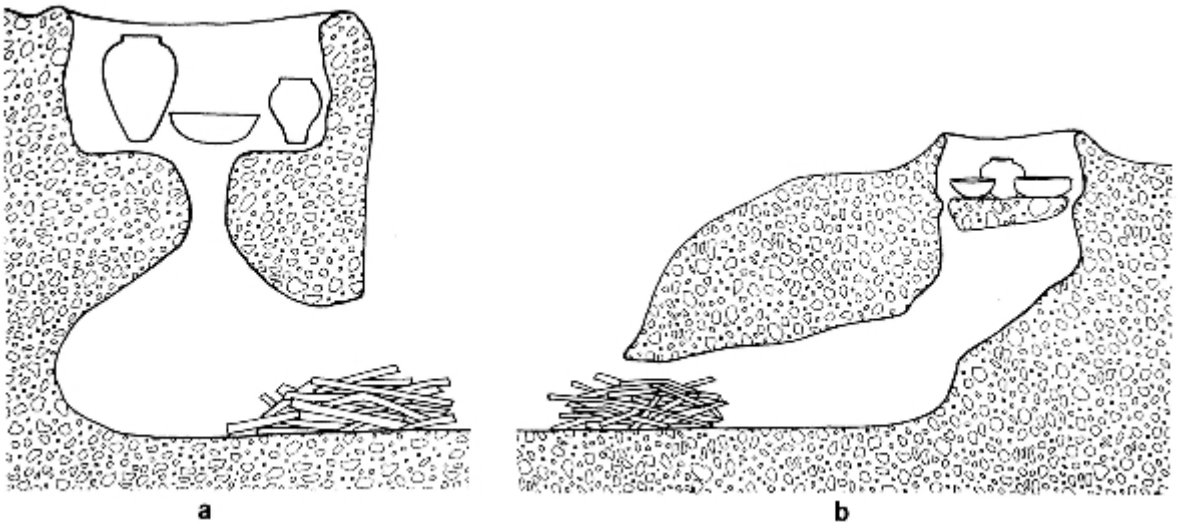

Figure 1.3 Reconstruction of early bank kilns at Banpo, China: *a*, vertical kiln; *b*, horizontal kiln. After Shangraw 1977: 389.

One of the most beautiful Chinese wares is celadon, identified by its distinctive sea green, apple green, or olive green glaze. Although celadon glaze manufacture has been dated as early as the fourth century AD (Mikami 1979: 12), the most famous of the celadons were those produced in the Longquan (Lung Ch'uan) District of the Southern Song dynasty (AD 1127–79) and later (Hobson 1976: 16; Li Hu Hou 1985; Vandiver and Kingery 1984). Celadons were popular throughout Asia, not only because of their beauty but also their supposed magical or curative powers. It was believed in India and Persia, for example, that a celadon bowl would crack or change color if its contents

were poisoned, and medications were thought to be more powerful if prepared in a celadon vessel or if such a vessel or its glaze were ground and mixed into the potion (Spinks 1965: 98–100).

Chinese pottery and porcelains exerted incalculable influence on the ceramic industries of other nations for more than a millennium. The earliest evidence for long-distance export of Chinese products comes from the time of the T'ang dynasty, when early porcelains became popular among the Asian aristocracy (Mikami 1979: 35). Trade contacts with the Islamic Near East flourished via the Silk Road during the T'ang and Yuan dynasties, and T'ang *sancai* (three-color) glazes influenced the predecessors of Mediterranean majolicas. Chinese potters imported cobalt from their Muslim trading partners (Zhang Fukang 1985: 173) and eventually developed the blue-on-white porcelain tradition that has continued to the present (see Weiss 1971: 26–29). Celadons reached Korea by the eleventh century (Mikami 1979: 13) and porcelains arrived there in the fourteenth century. Most of the Chinese export porcelains (Gordon 1977; Weiss 1971: 44–46) shipped to Europe and the Americas in the sixteenth century and later were manufactured at Jingdezhen.

1.3.2 Western Asia/Near East

In various areas of the Near East, pottery containers appear to have been preceded by carved stone bowls (Hayden 1998: 29). Clays were used for varied purposes after about ten thousand years ago in subareas of the region. In the Jordan Valley in the southern Levant, for example, large early Pre-Pottery Neolithic settlements featured communal granaries and other storage facilities constructed of tempered clay, located between domestic structures and used for storage of wild plant resources (Kuijt and Finlayson 2009). Pottery is known from the Pre-Pottery Neolithic B period: a marly clay tempered with herbivore dung (Biton et al. 2014). In the Zagros area, figurines, seals, tokens, small unfired dishes, and geometric cones, spheres, and disks were made of clay as early as 8500–7500 BC (Moore 1995; Schmandt-Besserat 1974; Simpson 1997) and pottery appeared at Ganj Dareh around 10,000 cal. BP (Bar-Yosef and Meadow 1995: 79). At Çatalhöyük in Anatolia fired clay objects are known around 7400 cal. BC, with fired, straw-tempered pottery containers beginning 400–500 years later (Hodder 2012: 152–53). Apparently used to cook with clay balls (a variant of stone-boiling), these small, thick vessels were replaced by larger vessels with mineral inclusions. Painted decoration on pottery became widespread later (Hodder 2012: 153–56; Zeder 2009: 17).

Early pottery appears to have been influenced by the pyrotechnological knowledge of calcining lime for plaster-making and by architectural uses of clay (Moore 1995: 45–46; Vandiver 1987; see also Kingery 1996: 190–94). The earliest manufactured containers in the region were large built-in storage jars made of layers of plaster and small *vaiselles blanches* made of a mixture of plaster and ash. Architecturally, clay was

used by itself or mixed with chaff or straw as poured or puddled adobe for constructing the walls, floors, and roofs of permanent houses and other structures. Adobe bricks began to be used as early as 7500–6300 BC in the Zagros area (Schmandt-Besserat 1974). Planoconvex bricks, formed in a mold and dried in the sun, continued to serve in the construction of residences, temples, and burial chambers for millennia; fired bricks were probably regularly in use by 1500 BC.

Early pottery was formed by a technique called "sequential slab construction," perhaps analogous to building with adobe or mud brick (Vandiver 1987). Pots were scraped, paddled, or rubbed to produce an even finish and fired in open bonfires, using wood or dung cakes for fuel. These and later vessels occur in a range of shapes, including bowls, cups, and trays, and were subsequently decorated with paint and incised lines. Decoration depicts a variety of plant and animal forms (fig. 1.4), human activities, and costuming; and the contexts of recovery—burials, household activity areas, refuse deposits—provide clues to their diverse functions.

Figure 1.4 Painted Samarran-ware bowl from Hassuna, a sixth-millennium BC village in Iraq. After Redman 1978b: fig. 6-9.

Other artifacts manufactured of low-fired and unfired clay include spindle whorls and loom weights for spinning and weaving; clay sickles with inset stone blades for harvesting grain; and female figurines with presumed connections to fertility or household ritual practices. Clay tokens and seals inscribed with various notations may be "administrative artifacts": records of economic transactions in which the varied sizes and shapes of the objects (cones, disks, etc.) might correspond to kinds and quantities of goods. These tokens have been linked to the development of writing (Schmandt-Besserat 1978; cf. Lieberman 1980) because their shapes are echoed in the earliest examples of cuneiform script on clay tablets dating to the late fourth millennium BC. When fired, whether intentionally or accidentally, as at Ebla (Tell Mardikh), these clay tablets formed a permanent "library" of knowledge and activities of the time (Matthiae 1977).

Kilns were developed early in the Near East, with a double-chamber vertical downdraft kiln known as early as the late seventh millennium BC (Majidzadeh 1975–77: 217; Simpson 1997: 38–39). In the fourth millennium BC, potters employed the rotary motion of a tournette-like "slow-wheel" device to smooth and finish certain kinds of ritual vessels (Roux 2003; Roux and de Miroschedji 2009). Pairs of such socketed hand wheels of stone or clay seem to have been common in the Near East after about 3500 BC (Amiran and Shenhav 1984; Lobert 1984), and a later potter's workshop using pivoted stones was found in a cave (Magrill and Middleton 1997). The true potter's wheel, in use by the Middle Bronze Age (after c. 2250 BC), allowed rapid mass production of standardized forms and development of a ceramic industry serving a large market (but see Magrill and Middleton 2001).

Lead glazes were in use by 2500 BC (Rhodes and Hopper 2000: 204) and alkaline-glazed pottery manufacture may have begun about the sixteenth century BC (Hedges and Moorey 1975). Tin-lead glazes (or enamels) were used to decorate brick panels by the Assyrians after 900 BC, but knowledge of their manufacture may have been lost until rediscovery by ninth-century AD Islamic potters trying to emulate T'ang porcelains. Tin-glazed pottery and tiles were produced throughout the Arab world, knowledge of their manufacture traveling westward with the Muslim conquest of Spain and Italy, and later to the New World in the sixteenth century.

1.3.3 Africa

Early evidence of pottery manufacture comes from a broad swath of North Africa lying in or immediately south of what is now the Sahara Desert. This area was, in the early Holocene, a well-watered grassland, and the Nile valley was a rich environment for hunters and collectors, with mammals, fish, and fowl in addition to plant foods. The earliest pottery known thus far comes from Mali in the tenth millennium BC. With a

calibrated pre-9400 BC date, this material was apparently used in boiling grains from wild grasses (Huysecom et al. 2009). Pottery dating c. 9500–8000 bp is known from eastern Africa (the middle Nile valley) and appears to be associated with semi-sedentary foragers (Close 1995; Welsby 1997: 27; see also Jördeczka et al. 2011). This early North African pottery was generally well made and fired, some with comb- or cord-marked interiors or rocker stamping, and in a variety of forms (Close 1995: 26–31; Welsby 1997: 28, 30–31). Quantities varied from scarce, with probable "social and symbolic" uses, to abundant, functioning in cooking, storage, and mortuary activities.

Sedentary, pottery-producing villages appeared in the middle Nile valley in the seventh millennium BC, and for the next several thousand years of the Predynastic period varied burnished redware and blackware vessels were produced throughout the valley (Spencer 1997). Vessels were hand-built or turned on a "slow wheel." Lipid analysis of residues in pottery from a late fifth millennium rockshelter in Libya yielded evidence of early dairying (Dunne et al. 2012).

An early technological achievement was the compounding of a vitreous quartz-based material known as faience or Egyptian paste during the Predynastic period, about 4000–3100 BC (Vandiver 1982). With a sodium-based self-glaze typically colored turquoise by the presence of copper, Egyptian faience was used for beads and other jewelry as well as small molded vessels (Cooper 2000: 29–30). The true potter's wheel (kick wheel) began to be used in the fifth century bc.

1.3.4 Europe and the Mediterranean

Europe was not an independent center of pottery development. The appearance and development of pottery in eastern Europe appears to have arrived independent of farming (Dolukhanov et al. 2010), contrary to the traditional "wave of advance" model, and in western Europe it is related to complex movements and interactions of hunter-gatherer-fishers and farmers (Combé 2010).

Figure 1.5 Greek red-figure vase showing painters at work. Courtesy of Joseph V. Noble.

Two kinds of pottery in Europe and the Classical world, Greek figured pottery and Roman Arretine ware, represent outstanding technical achievements. Both wares, judged by their firing and other characteristics, are high-fired terracottas or low-fired earthenwares. Neither is glazed, though their fine glossy slips have sometimes been erroneously referred to as glazes.

Greek black- and red-figure pottery (Noble 1966; Richter 1976) was manufactured during the sixth through fourth centuries BC in Athens. The distinctive painted decoration (fig. 1.5) was applied by potters or by a separate group of vase painters who sometimes signed their work, and the painted scenes depict varied activities of Greek life, both ceremonial and quotidian (Beazley 1945; Boardman 2001; Thompson 1984; Von Bothmer 1985). The co-occurrence of both red and black iron paints and slips on these vessels entranced and perplexed scholars for generations, but experiments to reproduce them did not succeed until the early twentieth century (Schumann 1942; Stross and Asaro 1984: 181–83). It was found that the colors and gloss of the paint derived from a particular clay mineral (illite) and from careful control of kiln atmosphere during firing.

Roman Arretine ware dates from the first century BC to the fourth century AD, the name coming from ancient Arretium (modern Arezzo), a center of production in northern Italy. These beautiful lustrous red bowls and jars were copied at multiple centers of manufacture (Johns 1977a; Peacock 1982: 114–28) and were widely traded throughout

Roman Europe. Wares made in what is now France and Germany, for example, are referred to as Samian or Gaulish Samian (from Samos) ware (fig. 1.6) or as *terra sigillata* ("earth/clay stamped with designs"). Like the Greek gloss paints, the distinctive red slips of Arretine and Samian wares are fine illite clays fired in a carefully controlled atmosphere at temperatures between 980°C and 1260°C (Bimson 1956; Lawrence and West 1982: 212; Tite et al. 1982). Vessels were formed in wheel-thrown molds and often feature the name or mark of either the vessel maker or the mold maker on their surface (Hoffman 1983).

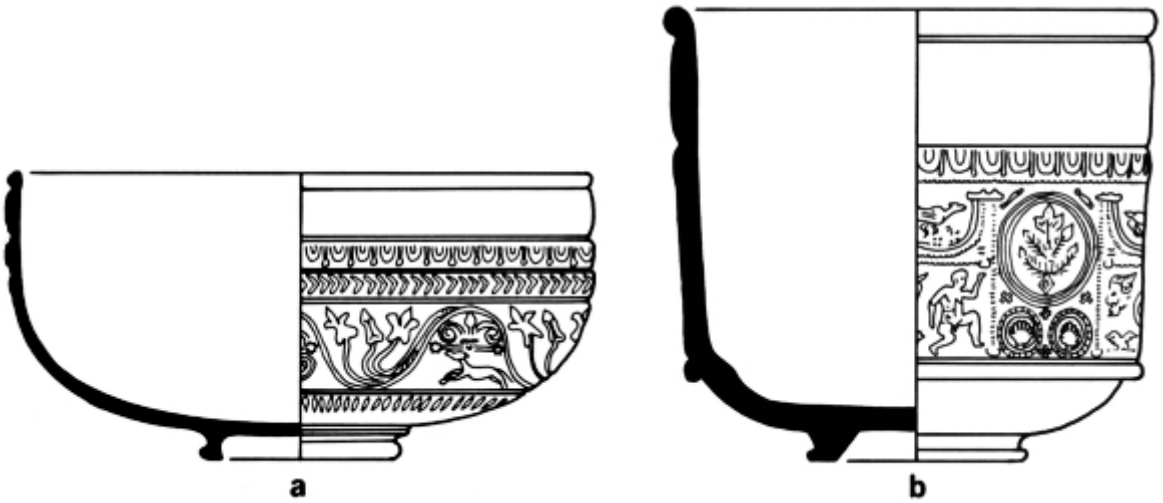

Figure 1.6 Gaulish Samian-ware bowls, moldmade with raised decoration and covered with a red slip: *a*, hemispherical bowl (form Drag 37), third century BC; *b*, slightly less common deep bowl (Drag 30), first and second centuries BC. After Anderson 1984: fig. 27.

In the early eighth century AD, Islamic expansion throughout the Mediterranean region introduced the technique of coating fine earthenware bodies with opaque tin enamels. Cream-to-white tin-lead glazes had been used in Persia (modern Iran-Iraq) in imitation of T'ang wares, which were moved over land and water by Arab traders in China. With Muslim expansion, this practice of opacifying glazes spread westward into northern Africa and southern Europe (Gavin et al. 2003), flourishing particularly in Italy and the Iberian Peninsula where the ware came to be known as *maiólica* and *mayólica*, respectively. In Spain, some of this pottery maintained the traditional early Islamic copper green and manganese purplish-brown decoration, whereas producers in the southeastern peninsula began painting with pigments that attained a metallic luster, an innovation brought by Egyptian potters fleeing the ruling dynasty's collapse. Later innovations, known as the Italianate or Renaissance style, introduced polychrome decoration featuring blue, yellow, and orange alongside green and black in flowery motifs (Kingery 1993). Major production centers emerged in Talavera and Seville (e.g., Pleguezuelo 2003).

The technology of tin-enameling and its decorative styles spread into northern Europe, where they became known by several names: faience (Faenza) for Italian imports (not to be confused with the much earlier Egyptian faience) and Delft (Fourest 1980) in the Netherlands. These wares, like those of Spain, were heavily influenced stylistically by blue-on-white Chinese porcelains imported through Spain's and Portugal's maritime ventures to Asia. While tin-enameled ware was undergoing its transformations, lead-glazed wares continued to be made throughout Europe with various kinds of ornamentation, and by the fourteenth century Germany had taken the lead in producing well-developed stoneware.

When Chinese porcelains of the Ming and later dynasties reached Europe, potters there tried various experiments to achieve the same hardness and translucency (see Weiss 1971: 60–83), including adding ground glass to the clay, but they were hindered by a lack of suitably plastic and white-firing kaolins. The translucency could be achieved but not the hardness, and the European product through the seventeenth century was a "soft paste porcelain" or *pâte tendre* (Kingery and Smith 1985). Although an experimental porcelain had been made by Grand Duke Francesco Maria de' Medici in Italy in the late sixteenth century (Kingery and Smith 1985; Weiss 1971: 69; Wykes-Joyce 1958: 78–79), it was not until the early eighteenth century that a viable product was achieved. Two Germans, "alchemist" Johan Friedrich Böttger and physicist Walter von Tschirnhaus, working under the orders of the king of Poland, found a local source of kaolin clay that permitted them success in creating a hard, white, translucent porcelain body—a success achieved, according to Böttger's (?) notes, at 5:00 p.m. on January 15, 1708, after a twelve-hour firing (Queiroz and Agathopoulos 2005; Weiss 1971: 60). Following that discovery, a royal porcelain factory was later established at Meissen, near Dresden (Wykes-Joyce 1958: 136–39). The French continued to produce soft porcelains at Vincennes (d'Albis 1985) and Sèvres until kaolin was discovered at Limoges in 1768, after which true hard porcelain soon began to be manufactured in that country. Porcelains today are composed of 40–50% kaolin (sometimes with the addition of ~10% ball clay for plasticity), 25–30% feldspar, and 20–25% quartz or flint (Norton 1970: 336; Rhodes and Hopper 2000: 95).

Beginning in the mid-eighteenth century, England industrialized its pottery manufacture and produced massive quantities of table wares, primarily around Staffordshire in the west-central part of the country (Cooper 2000: 226–43). Wedgwood jasper ware, with high quantities of barium sulfate, is a distinctive fine, hard, porcelain-like stoneware that began to be made in the mid-eighteenth century (Dolan 2004). "Bone china" is a later innovation by Josiah Spode, who added calcined ox bones to a porcelain-like fine stoneware body formula and achieved the desired translucency. Bone china, consisting of 40–50% bone ash, today is made almost exclusively in England (Norton 1970: 346–60; Weyl 1941).

1.4 Pottery and Ceramics in the "New" World

In the Western Hemisphere the development of pottery proceeded independent of that in the Old World, from unrelated areas of origin, and variably in time and mode of occurrence. The extent to which low-fired or unfired clay objects might have been used by early, pre-agricultural hunter-gatherers in a widespread "software horizon" is unknown. However, hunting-gathering groups made pottery in the Great Basin area of the western United States in late pre-Columbian times (Eerkens et al. 2002) and unfired fiber-tempered vessels were used by Eskimos from AD 1000 to 1600 (Stimmell and Stromberg 1986: 247).

Fired clay containers appear to have had multiple independent origins, and unfortunately little is known of what kinds of clay use, if any, might have preceded pottery's development. Two facts are striking about the history of pottery in the Americas. One is that its earliest appearance is considerably later than in the Old World, by five thousand years or so. Second, two of the hallmarks of Old World ceramic production, glazes and the potter's wheel, never appeared in pre-Hispanic times. Although semi-subterranean firing facilities have been identified in far more areas than previously supposed, kilns do not appear to have been ubiquitous (or have not survived). In general, most New World pottery seems to have been fired in the open with temperatures in the range of 700–900°C (see Shepard 1976: 84, 87).

Lacking the wheel and high-temperature kilns, New World potters were rarely able to attain the same levels of technical achievement as did their Old World contemporaries. For example, stonewares and porcelains were never manufactured in the indigenous New World, perhaps because in the general absence of kilns the consistent high temperatures necessary for vitrification could not be sustained. Whatever the reason, all New World aboriginal pottery falls into the categories of terracotta and earthenware.

Pottery vessels made in the ancient New World included the familiar repertoire of cooking, serving, and storage vessels with local variations on shape and embellishment. In addition, special vessels for burning incense, burial urns, braziers, griddles for toasting tortillas or manioc cakes, and "chile grinders" (bowls with incised interiors for grinding chiles and other vegetal materials) were common. Other fired-clay objects included figurines, spindle whorls, fishing net and line sinkers, smoking pipes, beads and other ornaments, and musical instruments such as whistles, drums, flutes, and rattles. The artistic and utilitarian excellence of New World products is entirely the equal of Old World pottery, and outstanding examples of the potter's craft can be found throughout.

1.4.1 South America

The earliest pottery in the Western Hemisphere appears to come from the Amazonian tropics of what is today Brazil, with uncalibrated dates in the eighth millennium bp

(Roosevelt 1995: table 10.2; cf. Clark and Gosser 1995: table 17.1). This pottery, low-fired, sand-tempered, and formed of patches of clay rather than coils, is associated with intensive foraging in a riverine-estuarine environment. To the northwest in Colombia, fiber-tempered pottery, some of which was decorated, was found at seasonal encampments of foragers with diverse subsistence foci and dated about six thousand years ago (Oyuela-Caycedo 1995; Pratt 1999; Rodríguez 1995).

In the Pacific watershed of the Andes Mountains, pottery began to be regularly used quite late, following a long Archaic or Preceramic period. From roughly 10,000 to 4,000 years ago, the subsistence practices of coastal peoples in semi-sedentary and sedentary villages focused heavily on maritime resources (Moseley 1975). Plants and animals were domesticated along the coasts and in the highlands alike, but pottery was not used. Interpretations of early pottery from Valdivia, on the coast of Ecuador, at first linked it to Jomon pottery from Japan on the basis of decorative similarities (Meggers and Evans 1966). This prompted speculation that a group of Japanese fishermen were blown off course and shipwrecked in this area and convinced local inhabitants to make what was then thought to be the first New World pottery. Subsequent excavations, however, revealed an earlier pottery style stratigraphically below the Jomon-like material (Bischoff and Viteri Gamboa 1972), and this idea was no longer given credence (Damp and Vargas 1995). A recent genetic study, however, identified a distinct link between small groups in Ecuador and Asia that may have begun 6000 years ago, reviving this possibility once again (Roewer et al. 2013).

Adobe bricks were commonly used in ceremonial buildings on the Peruvian coast, as early as the Initial Period (about 1800 BC) at the northern site of Las Haldas, whereas in the highlands stone was more typically used. Pottery was not widely made and used in the Andes until the Initial Period, dated 1800–900 BC, along with agricultural intensification through irrigation technology (Rodríguez Kembel and Rick 2004: 52–53). Presumably containers of perishable materials had sufficed for domestic and other purposes in this arid climate until this time. Amazonian-style pottery appears at the highland Peruvian site of Kotosh around 1800 BC (Dillehay et al. 2004: 31); fiber-tempered pottery occurs relatively late, during the early first millennium BC.

Later in coastal Peru, from 200 BC to AD 700, Nazca (Proulx 2006) and Moche (Jackson 2008) potters produced splendid vessels, some molded and some modeled, featuring painted houses, animals, plants, and human faces so individualized as to suggest portraits (fig. 1. 7). Multicolored designs included red, black, brown, yellow, blue, green, pink, and white. These and other elaborate polychrome vessels, decorated with geometric and stylized natural motifs, were made throughout the Andes up to the coming of the Spaniards (see Shimada 1994a, b). Huge urns were used for burials in some areas, the deceased being placed inside in a flexed or fetal position; elsewhere, smaller vessels often held cremated remains.

Given Andean skills in working with metals—gold, silver, copper (e.g., Lechtman 2007)—at high temperatures, it is not surprising that kilns were used in firing pottery.

On the north coast of Peru, clusters of kilns nearly 2500 years old have been identified and some have been experimentally rebuilt and refired (see Shimada 1997; Shimada et al. 2003a, b, c, d). Other kilns are associated with pre-Inka and Inka settlement in Catamarca, northwestern Argentina (de la Fuente 2011).

Figure 1.7 Moche portrait vessel, Peru. Peabody Museum, Harvard University, photographed by Hillel Burger. Copyright by the President and Fellows of Harvard College, 1985, all rights reserved.

1.4.2 Mesoamerica

Currently available dating suggests a south-to-north chronological sequence of the appearance of early pottery through the Central American isthmus and into Mexico (Cooke 1995; Hoopes 1995). This suggests diffusion: adoption of the ideas and skills underlying pottery manufacture, perhaps a consequence of actual pots circulating through social interactions (Clark and Gosser 1995: 209). Early pottery in Panama

dates as early as 4500–4000 BP, with that of the Monagrillo culture on the Pacific side of the isthmus looking like "a first attempt to make clay pots" (Cooke 2005: 143).

In Mexico, early pottery has been recovered from contrasting environments: moist Pacific lowlands and arid highland valleys (Brush 1965; Clark and Gosser 1995; Flannery and Marcus 1994). Early containers were relatively simple forms that often echoed the shapes of gourds, sometimes decorated with incising or a red wash. The distinctive Early Formative neckless jar form known as a *tecomate* might have been associated with non- or semi-sedentary settlement (P. Arnold 1999).

Potter's wheels were not known in pre-Columbian Mesoamerica, although several devices—such as the *kabal* in Yucatán (Thompson 1958) and the *molde* in Oaxaca (Foster 1959)—were used by potters to turn the vessel during forming. Around 1000 cal. BC in central highland Mexico, lime was calcined in small pits (Castanzo and Anderson 2004), and pottery was fired in various arrangements, including updraft kilns at Monte Albán (Elson and Sherman 2007) and Veracruz (Santley et al. 1989). In the Maya area of eastern Mesoamerica, other than facilities for calcining lime for plaster (e.g., at Copán; Abrams and Freter 1996), a kiln of uncertain function in northwestern Honduras (Urban et al. 1997), and the possible use of sherd-lined pits for firing pottery (Hammond and Kosakowsky 1991), little is known of firing arrangements.

In Mesoamerican architecture, stone was employed far more often than adobe. Adobe bricks were used in ceremonial construction at Oaxaca during the Late Formative period (c. 900–800 BC; Flannery 1976: 24). Fired bricks are rare, particularly associated with the Late/Terminal Classic (c. AD 600–900) site of Comalcalco, in Tabasco, Mexico. Ceramic-lined wells are known from Quirigua, Guatemala, and elsewhere in the Maya region (Ashmore 1984).

Potters of the Classic-period Maya civilization, AD 200 to 900, produced an array of bowls and vases with modeled, incised, and polychrome painted decoration of exceptional technical skill. Late Classic cylindrical vessels and plates portrayed human and animal figures in a graceful natural style, revealing ritual and mythical (fig. 1.8) activities such as dances, processions, or royal audiences, often with a brief formulaic text that identified the person for whom the pot was made (Coe 1973, 1978; Just 2012; Reents-Budet 1994; Robicsek and Hales 1981). These were painted with subtly toned pigments, sometime resist applied, on a light-colored underslip and covered with a translucent, glossy overslip. The absence of fireclouds suggests that they were probably individually fired inside larger pots serving as saggars.

Plumbate is a distinctive ware widely traded during the early Postclassic period (c. AD 1000–1250). Named for their shiny, lead-colored appearance, Plumbate vessels often feature elaborately modeled semi-effigy figures or faces. Although the ware is sometimes mistakenly thought to be glazed, it is finished with a clay-rich slip or "slip-glaze," the silvery color resulting from peculiarities in composition (high iron) and firing that brought about vitrification in places (Neff 2003; Neff and Bishop 1988; Shepard 1948a).

Anthropomorphic and zoomorphic figurines have a long history of manufacture in Mesoamerica. In Mexico as in parts of the Old World, clay figurines preceded clay containers, with crude human representations found at a Late Archaic (pre-ceramic) base camp near Mexico City in a level dated to 2300 bc (Marcus 1998: 39, citing Niederberger 1976). Later modeled and moldmade figurines of humans and animals were found throughout the region, with complex modeled and painted tableaus of houses, villages, and dancers deposited in burials in western Mexico.

Figure 1.8 Late Classic lowland Maya polychrome tripod dish, known as the "Resurrection Plate." It depicts a scene from the *Popol Vuh* creation myth, in which the Hero Twins resurrect their father. Photograph K1892 © Justin Kerr.

Mesoamerican incense burners (*incensarios*) were often elaborated with modeled and painted faces of anthropomorphic and zoomorphic supernaturals. At Teotihuacan in highland Mexico the lids of the receptacles for burning resins supported a scaffolding for interchangeable moldmade elements; at Classic Palenque, in the Maya lowlands,

ornately modeled and painted cylindrical stands supported the receptacles; in Oaxaca (fig. 1.9) and the Postclassic Maya lowlands, modeled figures were attached to the front of plain bowls or vases that held the incense (Milbrath 2007). Openings were typically placed so that smoke would emerge from the figure's nose and mouth.

Figure 1.9 Zapotec effigy urn from Oaxaca, Mexico, depicting the god of rain and lightning. These urns, which usually have a cylindrical vase behind the effigy figure, are approximately 45–60 cm in height and were placed in tombs during the Classic period (ca. AD 200–700). After Willey 1966: fig. 3-96.

1.4.3 North America

The Southeastern United States, particularly the Atlantic and Gulf coastal plains, appears to be a center of independent invention of pottery containers. These are primarily software-type vessels, low-fired and often fiber-tempered (Saunders and Hays 2004). This pottery, which began to appear around 5200–5000 years ago along the

coast of Georgia and Florida, consisted of flat-bottomed bowls that mimicked the shape of steatite containers and were used for indirect-heat cooking (stone boiling) (Sassaman 1993, 1995, 2004). About a millennium later, fiber-tempered pottery was being made and used in the central United States by hunter-gatherers (Reid 1984).

Varied plastic decorative techniques, especially incising and modeling, rather than painting, were the outstanding modes of embellishment in the southeast. Modeled heads of dogs or birds were often added to rims of simple globular vessels (fig. 1.10), or the vessels themselves might be in human or animal form, with features accented by paint and incising (Cherry and Mainfort 2009; Knight and Steponaitis 2007; Pluckhahn and Cordell 2011: fig. 2).

In the arid Southwestern United States, patterns of early clay use resemble those in Eurasia, with unfired anthropomorphic figurines and other objects of clay recovered from Early Archaic (c. 5600–5000 BC) levels of caves in Utah (Coulam and Schroedl 1996). Small "incipient" plainware vessels, possibly with ritual uses, were used in southeastern Arizona around 2100 BC (Heidke 1999). Utilitarian pottery containers were produced much later, with the earliest dates around 800 BC (Bayman 1999: 259; Heidke 1997; Heidke and Habicht-Mauche 1998). In the Colorado Plateau (Four Corners) area, although clay containers had long been used in surrounding areas, the earliest pottery was used by semi-sedentary pithouse dwellers around AD 200–400. Vessels included neckless globular jars, known as seed jars, with interior spalling suggestive of fermentation (Skibo and Blinman 1999: 182–83), raising the possibility of community feasting.

Figure 1.10 A Weeden Island pot from the McKeithen site (8CO17) in north Florida, ca. AD 500. Two dog heads and one bird head face inward; one bird head with a missing beak faces outward. Height to top of heads, 20 cm. Collections of the Anthropology Division of the Florida Museum of Natural History, FLMNH cat. no. A-10952.

Figure 1.11 Zuni jar from New Mexico, painted black and red on white; height 26 cm. Florida Museum of Natural History cat. no. P-1861.

The beautiful pottery of the late Pueblo, Salado, Mimbres, and Hohokam cultures of the Southwest featured geometric and stylized life-form representations with polychrome or black-and-white painted decoration (fig. 1.11) (Crown 1994; Dittert and Plog 1980; Hayes and Blom 1996; Hegmon 1995; LeBlanc 2005). Surfaces of aboriginal vessels were covered by clay-rich slips, although vitreous glaze paints were produced after AD 1300 (Habicht-Mauche et al. 2002; Shepard 1942a). Some of this pottery, particularly black-on-white ware, was fired in large trenches, perhaps as group efforts (Bernardini 2000; Blinman and Swink 1997). The Southwest's skilled potters continue to produce art for collectors the world over.

1.4.4 Pottery and Ceramics in the Colonial World

The prolonged European conquest of the native states and chiefdoms in their newly discovered world across the Atlantic had drastic social, demographic, and economic consequences—famines, disease, settlement relocation, enslavement, and depopulation. The impacts of conquest also affected ceramics. Old World products were imported, including the traditional Mediterranean transport and storage vessels known as olive jars or *botijas* (Goggin 1970), majolicas, and Asian porcelains. Northern European ceramics, including transferwares, queen's ware, creamware, pearlware, ironstone, and

stoneware were shipped to the Americas (see Majewski and O'Brien 1987; Spencer-Wood and Heberling 1987) and the Spanish colonies were able to obtain these goods after the 1778 Hapsburg lifting of import embargoes. These and other imports are recovered in excavations at missions, ports, trading centers, and settlements throughout the Americas.

Brightly colored, tin-enameled majolicas, long important in southern Europe, also played a role in the ceramic history of what would become the Americas (Lister and Lister 1982, 1987). With the establishment of colonial Spanish settlements, the technologies of majolica production were established around 1540 in Mexico and within a century they had expanded southward into what are now Central and South America (Rice 2013a, b, c). Although the term majolica is often used generically to refer to tin-lead glazed earthenware, strictly speaking it is a cultural term specific to the Spanish- and Italian-made products, as are delft and faience for wares produced in the Netherlands and France.

Another consequence of European conquest was a hybrid blending of traditions of resource use, form, and decoration (Card 2013). Although in many respects utilitarian pottery-making continued virtually unchanged from its pre-European patterns, in some areas there was a fusion of indigenous and introduced forms and technologies, resulting in what has been called "colonoware" (Wheaton 2002). Colonoware refers to vessels that are often made of traditional pastes but in forms, or with secondary form characteristics—handles, bases, and so on—that mimic those of nonlocal wares. Other combinations of traits are also found. The term comes from historical archaeology in the Southeastern United States, and was early used with respect to a mingling of native with African pottery traditions, but it can also apply to the addition of European traits.

As European settlers—chiefly Spanish, Portuguese, English, French, Dutch—and potters, and also African potters, arrived in the Western Hemisphere, they introduced the potter's wheel, kilns, and glazes, and stimulated local manufacture of glazed pottery and tiles for construction and trade. In so doing, these settlers transformed not only the products but also the organization of the indigenous ceramic craft in many parts of this vast region. Local sources of clays and other ingredients were identified and appropriated, and production centers emerged in or near the new colonial population centers to meet their needs for containers and table service. Regrettably, most of these have succumbed to the forces of modernization, but some survive to the present day.

Part 2

The Raw Materials of Pottery Making: Perspectives from Chemistry, Geology, and Engineering

> In an age that glorifies celestial mechanics, matters "of the earth, earthy" have to be etherealized before they appeal to earthlings. . . . Water, air, and fire—the admired constituents—can all be conceived as *pure*. But "pure earth" seems to be a contradiction in terms, earth being the one unpurifiable element that sullies everything else. My subject being a turbid mixture of earth and pure water . . . I find the public preoccupation with unearthly problems a little unrealistic; but it warns me not to try to make mud glamorous.
>
> Deevey 1970: 5

The pottery fragments recovered in archaeological excavations contain vast amounts of coded or encrypted information about their makers and users. How to break the codes and read the clues? Understanding the human behavior behind the manufacture and use of ancient pottery begins with an understanding of the resources used and their properties, the primary resource being clay. But pottery making involves untold ways of manipulating the clay—cleaning, pounding, wetting, shaping, drying, firing. These procedures are universal in some senses, but in other senses they are highly variable from place to place and culture to culture. These variations, which the archaeologist seeks to understand, are adaptations to the resources available to the potter, to make a strong pot that conforms to his or her standards and those of its users.

The chapters in Part 2 establish the foundations for understanding the fired and often broken fragments of pottery that abound at post-Pleistocene archaeological sites around the world. These properties also guide the technological choices underlying potters' behavior in the "ethnographic present." Thus Part 2 begins with the raw materials—clays and their origins—and moves to modification of their properties through the addition of water and other constituents, and the changes that clays and glaze coatings undergo during drying and firing. Unless otherwise specified, the discussion focuses on what might be called "natural" clays: fine plastic materials of varied origin and composition that can be shaped into a desired form and hardened with heat.

2 Clays: Origins and Definitions

> We are interested in clay not so much for what it is in the natural state as for what it may become.
>
> Rhodes 1973: 13

Of all the materials and processes involved in making a pottery bowl or jar or dish, the most important are clay and its manipulation. Clays are complex substances. It is of little use to minimize this complexity, for it is clays' very diversity that enhances their desirability as raw material and leads to the variety of objects that can be manufactured from them (Staubach 2005; Velde and Druc 1999). An understanding of clays and their diversity begins with review of some basic principles of geology and geochemistry that underlie the origins and properties of clays.

2.1 Earth Materials

The planet Earth may be envisioned as a series of concentric zones—the core, the surface, and the surrounding air. The core comprises three subzones, composed of mixtures of iron, nickel, silicon, and magnesium; it is more than 6,000 km thick and its center is presumed to be molten and fluid. Overlying this core is a thin (average 24–32 km) crust known as the lithosphere (Gk. *lithos,* stone), composed of rocks and sediments. Above the crust is the atmosphere, consisting of various gases, including oxygen. In studying clays, the most important of these zones is the lithosphere, its composition and formation.

The lithosphere or crust is composed of chemical elements such as the metals aluminum (Al) and iron (Fe), and the metalloid silicon (Si) (fig. 2.1). These elements do not exist as free aluminum or silicon but instead are typically combined with other elements to form chemical compounds. The most common of such compounds incorporate oxygen, the most abundant element in exposed rocks, to form oxides. Table 2.1 shows the composition of the Earth's crust in oxides of common elements. Oxygen combines with other elements such as carbon (C), sulfur (S), and hydrogen (H) to form additional oxides that are gases or liquids rather than solids: for example, CO_2, SO_2, and H_2O.

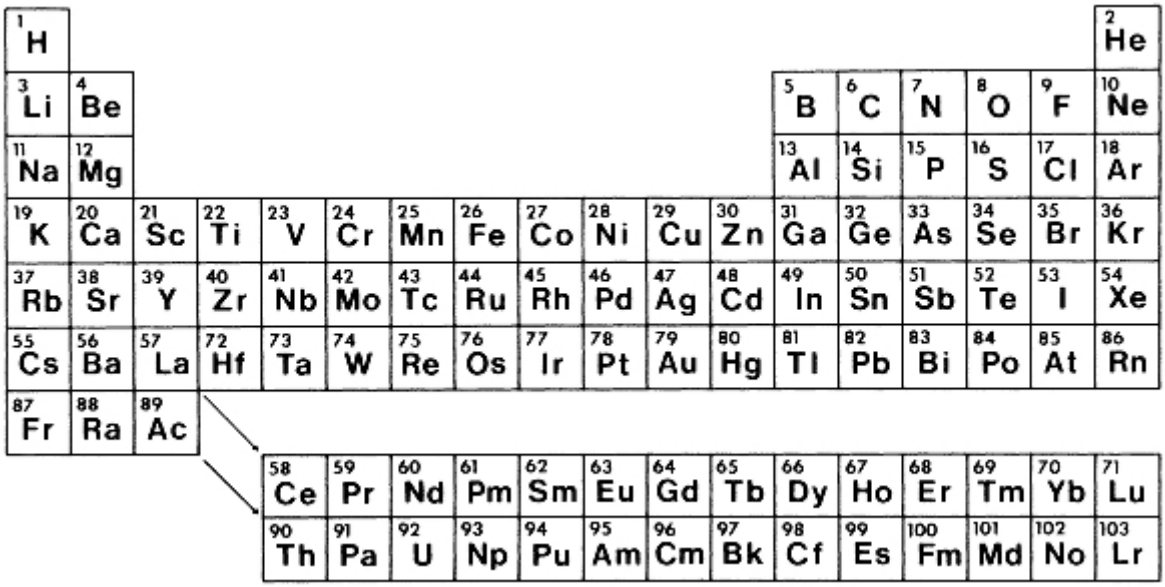

Figure 2.1 The periodic table of the elements, showing element symbol and atomic number (upper left corner).

Table 2.1 Composition of the Earth's Upper Continental Crust (Percentage by Weight)

SiO_2	66.62
Al_2O_3	15.4
FeO	5.04
CaO	3.59
Na_2O	3.27
K_2O	2.8
MgO	2.48
TiO_2	0.64
P_2O_5	0.15

Source: After Rudnick and Gao 2003: table 1.

Elements, oxides, and other compounds combine in various ways to form minerals. A mineral is a homogeneous, inorganic solid with a characteristic chemical composition and an ordered structure of its constituent atoms. This systematic arrangement is referred to as the crystal or crystalline structure and all minerals, because they exhibit one of several kinds of atomic ordering, are crystalline. Substances that lack these regular or periodic atomic arrangements are described as amorphous. Besides their crystalline forms, minerals may be distinguished by characteristic properties of specific gravity, hardness, fracture, color, and luster. Some of these properties are visible to the unaided eye, whereas others can be measured only with complex instrumentation.

Minerals may be described or classified in many ways that are useful to archaeologists (Rapp 2002). For example, ore minerals—those that can be processed to yield iron ore, copper ore, gold ore, phosphate, and so forth—can be distinguished from rock-forming minerals. In studying clays it is appropriate to focus on rock-forming minerals, because all clays are products of the breakdown and decomposition of rocks (Righi and Meunier 2010).

2.1.1 Rock-Forming Minerals

The most common rock-forming minerals in the earth's crust are silicates: minerals with silica, SiO_2, as a major part of their composition. Although some rocks comprise only one such mineral, typically several of them combine. These minerals may be differentiated as essential, that is, the major constituents of the rock, and accessory, minor components that occur in small but distinctive amounts. It is easy to see, in table

2.1, that the most abundant rocks are silicates of aluminum, iron, calcium, sodium, potassium, and magnesium. Silicate minerals having these elements in their composition include feldspars, quartz, clays and micas, and ferromagnesian silicates, plus carbonates, in which CO_3 is a major component.

The most usual classification of rocks is by their origin: the familiar igneous, metamorphic, and sedimentary classes (see Bridge and Demicco 2008):

- Almost all rocks are derived from igneous sources (L. *ignis,* fire), that is, they formed from magma: molten silicate material under the earth's crust. Igneous rocks are differentiated into two principal categories, volcanic and plutonic, on the basis of where and how the molten material cooled:
  - Volcanic rocks, such as basalts and pumice, erupted or were extruded to the surface as lava or ash, then cooled rapidly, forming typically fine-grained material or glassy rocks such as obsidian.
  - Plutonic or intrusive rocks formed deep in the earth, cooled slowly, and are coarse-grained; examples are granites and diorities.
- Metamorphic rocks are igneous rocks transformed by heat or intense pressure or both.
- Sedimentary rocks (Tucker 2001) are primarily the result of transport and redeposition of the products of weathering of older igneous or metamorphic rock, although some kinds of sedimentary rock are organic deposits formed by compaction of shells or diatoms.
  - Potter's clays are sediments, but their ultimate origin is primarily igneous.
  - A large proportion of sedimentary rocks are classed as mudrocks, which are composed of at least 50% lithified mud—that is, clay minerals and other siliceous sediments with particle sizes less than 0.06 mm. Mudrocks include claystone, siltstone, mudstone, shale, and slate (Potter et al. 2005). (Muck is a term for another sediment, usually associated with wet environments and peat deposits, consisting of 50% or more fine organic matter.)

According to a new high-resolution global lithological mapping project (GLiM) of the exposed surfaces of the Earth's crust, the continents are covered primarily (64%) by sediments or sedimentary rocks, a third of which are carbonates (Hartmann and Moosdorf 2012). The remaining continental surfaces consist of 13% metamorphics and 13% igneous rocks (7% plutonic; 6% volcanic), with 10% of the exposed crust occupied by water or ice.

Igneous rocks, volcanic and plutonic, may be further described by their chemical composition on a continuum from felsic (acid) to mafic (basic). Felsic rocks (such as granites) are high in silica and have a light color and a low specific gravity. Mafic rocks have large quantities of ferromagnesian minerals, so named for their iron (Fe) and magnesium (Mg) content. These rocks, such as basalts, have less SiO_2 and are dark-colored and heavy, with a high specific gravity.

Within this continuum of felsic through mafic igneous rocks, the rock-forming minerals may be divided into several families. The most common of these are the feldspars, followed by micas, amphiboles (e.g., hornblende), pyroxenes (e.g., augite), and olivines. The distribution of these families among felsic versus mafic rocks is seen in table 2.2.

Feldspar, the most abundant mineral in the earth's crust, is an aluminosilicate; that is, it consists of alumina (Al_2O_3) and silica (SiO_2), with the relative proportion of SiO_2 varying from roughly 43% to 65%. Three additional elements—potassium (K), sodium (Na), and calcium (Ca)—are present in differing proportions and are responsible for the division of this mineral family into two major classes, alkali and soda-lime feldspars:

- Alkali feldspars contain varying amounts of potassium and sodium: examples are albite, anorthoclase, microcline, orthoclase, and sanidine. They have relatively high percentages of silica and are characteristic of more felsic rocks, occurring with quartz in granites, for example.
- The soda-lime or plagioclase feldspars (e.g., albite, andesine, anorthite, bytownite, labradorite, oligoclase) display varying amounts of sodium and calcium and are characteristic of the intermediate and mafic rocks such as diorites and basalt.

Table 2.2 Composition of Felsic through Mafic Igneous Rocks and Minerals

Felsic (>65% silica)	Intermediate	Mafic (45–55% silica)
Granite	Diorite	Gabbro
Rhyolite	Andesite	Basalt
	Syenite	
Quartz	. . .	. . .
K/NA feldspars, orthoclase	Plagioclase	Ca feldspars (plagioclase)
Muscovite mica	Biotite mica	Biotite mica
. . .	Hornblende	Amphibole (hornblende)
. . .	[Pyroxene]	Pyroxene (augite)
. . .	. . .	Olivine

2.1.2 Weathering and Clay Formation

Clays are sediments formed by weathering of silicate parent material, primarily at the earth's surface. Weathering involves physical/mechanical and chemical/biochemical agents and processes that bring about disintegration of that material, and these processes may occur separately or together. Physical mechanisms include abrasive forces such as wind, water (primarily rainfall but also flooding, percolating groundwater, wave or stream action), or glacial ice as agents of rock fragmentation and transport of fine particles (Bergaya et al. 2006; Righi and Meunier 2010; Velde 2010b). Chemical or hydrolytic weathering occurs in the presence of water, with solution, hydration, and oxidation processes leading to decomposition of the parent mineral(s). Chemical, biochemical, and biological agents, including acids (e.g., humic, carbonic, sulfuric), gases, algae, bacteria, and rootlet penetration, all play a part.

Rock-forming minerals, whether igneous or metamorphic, vary in their stability or susceptibility to such processes on the basis of their composition and texture. Table 2.3 lists eighteen common rock-forming minerals in order of most to least resistant to alteration. The rock-forming minerals that are most resistant to weathering are composed primarily of silica and alumina. Mafic minerals such as olivine, augite, and hornblende contain little alumina (or none, in the case of olivine), so they decompose easily, but because the ultramafic, basic rocks that comprise them contain little or no feldspar (silicate), they do not alter into clays. Even within these mineral families differences in stability are evident, as indicated by the relative positions of muscovite versus biotite mica and orthoclase versus anorthite (K- versus Ca-feldspar) in the

series. Thus it is the non-silica/non-alumina components of even the higher-alumina minerals, principally micas and feldspars, which alter most quickly, leaving behind the aluminosilicate: clay.

Table 2.3 Rock-Forming Minerals in Order of Resistance to Alteration

1. Quartz (most resistant)	10. Albite feldspar (Na/Ca)
2. Zircon	11. Oligoclase feldspar (Na/Ca)
3. Tourmaline	12. Andesine feldspar (Ca/Na)
4. Magnetite	13. Anorthite feldspar (Ca)
5. Ilmenite	14. Apatite
6. Rutile	15. Biotite mica
7. Muscovite mica	16. Hornblende (amphibole)
8. Orthoclase feldspar (K)	17. Augite (pyroxene)
9. Garnet	18. Olivine (least resistant)

The roles of mechanical and hydrolytic weathering processes vary not only with rock composition but also according to climatic conditions, and together they result in different kinds of clays. Processes are especially responsive to temperature (both mean and seasonal range) and rainfall. In cold or dry climates fragmentation predominates, with chemical weathering and decomposition being minimal. Mineral composition is altered relatively little, the principal weathering products being micas. In zones with extreme seasonality, the alternate freezing and melting of water that penetrates cracks in a rock is a major cause of disintegration: the change of water from a liquid to a solid at 0°C causes a ~9–10% expansion in volume at an equivalent force of up to 2000 pounds per square inch. During chemical weathering in the presence of water and free hydrogen ions, all the abundant minerals in igneous rocks except quartz break down, forming clay minerals, alkali and alkaline earth cations, and silica in solution.

In warm, humid environments hydrolysis is the dominant weathering process, as decomposition is largely a function of temperature, rainfall, drainage, leaching, and dissolution. High temperatures and high rainfall influence the plant cover, which in turn governs the acidity of the groundwater: plants release organic acids and CO_2 gas, which combines with moisture to form carbonic acid, a significant leaching agent. Thus leaching and chemical weathering preferentially remove elements from the rocks in accordance with their relative solubility—first sodium, then potassium, calcium, and magnesium, and finally silica—leaving weathered products that are rich in relatively insoluble iron and aluminum. The leached red, clayey, laterite soils of humid, tropical regions, as well as the high-alumina minerals gibbsite and bauxite, are products of such extreme hydrolysis.

2.2 Definitions of Clays

Clays are complex materials of practical use and academic interest in varied sciences and applied fields. Clays are studied by mineralogists, pedologists (soil scientists), agronomists, and engineers, which means that the material has been defined and described with respect to multiple standards and properties. These definitions may focus on clays' origin, their chemical or mineral composition, or their contemporary (commercial or industrial) usage. Each definition highlights a constellation of salient properties and characteristics relating to that particular viewpoint.

Acknowledging these varied views, the Clay Minerals Society defines clay as "a naturally occurring material composed primarily of fine-grained minerals, which is generally plastic at appropriate water contents and will harden when dried or fired" (http://www.clays.org/GLOSSARY/ClayTermsJune2012.pdf; 11; Guggenheim and Martin 1995: 255). This definition is basic and appropriate, but in the present context focused on pre- and non-industrial ceramics and their makers and users, the multiple discipline-specific definitions of clay yield further insights into the properties of potters' raw materials and their relations to the final products. "Clay" has multiple referents: a group of minerals, a category of rocks and soils in which these minerals predominate, and a particle-size grade that constitutes the major fraction of those minerals, rocks, and soils. The significance of these distinctions will become clearer through examination of five definitions of clays based on the following criteria: granulometry, depositional situation, chemical composition, mineralogy, and commercial usage.

2.2.1 Granulometry

The preceding definition of clay refers to it as fine-grained and a key attribute of clays is their particle size. Geologists, soil scientists, engineers, agronomists, and construction industry workers all characterize sediments by their granulometry, or the size of their constituent grains (see, for example, the Unified Soil Classification System used by ASTM International—formerly the American Society for Testing and Materials—standard ASTM D2487–11). Categories, from largest to smallest diameter, are gravel, sand, silt, and clay (fig. 2.2). Thus clay refers to the smallest or finest particle-size range of sedimentary materials.

In fact, clays were defined in the nineteenth century as the smallest grains that could be distinguished optically in a petrographic microscope: that is, crystallites less than about 2 micrometers (μm), or two-thousandths of a millimeter (0.002 mm) in diameter (Velde 2010a: 8). This limit is not absolute: the widely used Wentworth scale (Wentworth 1922, 1933) for classifying sediment particle sizes allows slightly larger grains in the clay range, setting the upper limit at 4 μm (or 0.004 mm) (see fig. 2.2). The upper limit of 2 μm is almost a natural boundary, however, because numerous analyses

of argillaceous (clayey) sediments have shown that clay minerals tend to be concentrated in a size fraction smaller than 2 μm, while non-clay minerals rarely occur in particles this tiny (Grim 1968: 2).

The small size of clay particles and their typically large surface area-to-volume ratio is the source of their most useful property, plasticity. Generally, the smaller the particles in a clay deposit or the greater the quantity of the smallest particles, the more plastic the clay. This extremely small size also gives clays the properties and behavior of colloids. Colloidal particles are extremely tiny, 1 μm (0.001 mm) or less in diameter, and a colloid is a mixture of such particles of a solid, liquid, or gas dispersed or suspended in another medium (solid, liquid, or gas). Examples of the colloidal state include fog (liquid dispersed in a gas), blood (solid in a liquid), and foam (gas in a liquid). Colloid-sized particles are at the lower range of clays, however, and not all clay-size particles are also colloid-size.

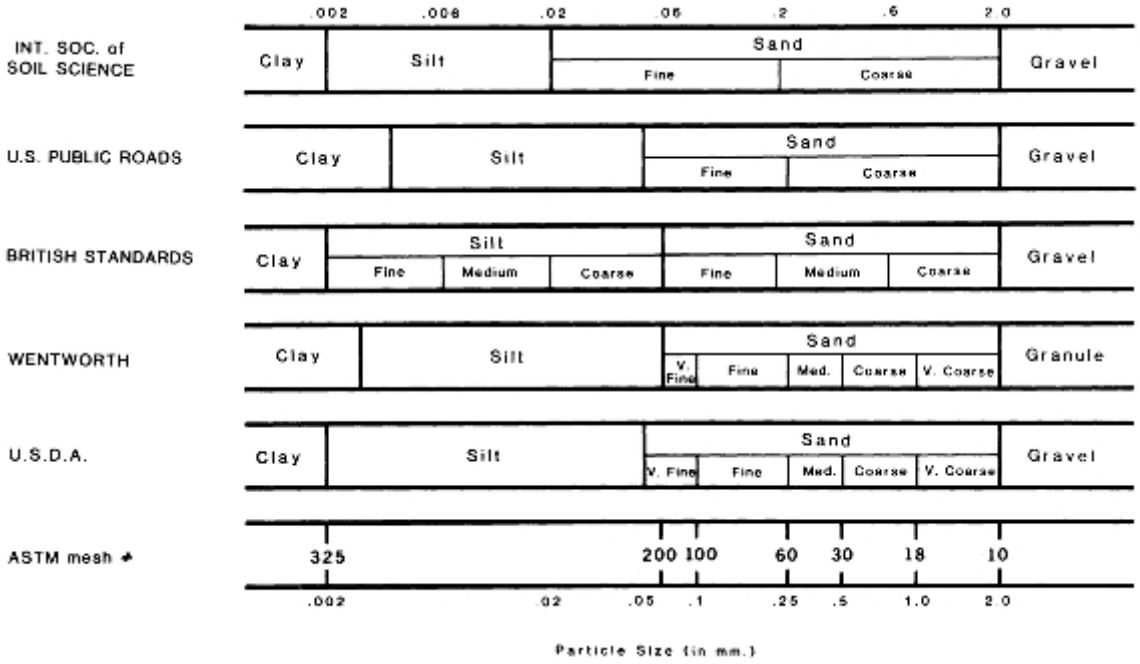

Figure 2.2 Six common standards for classification of particle sizes.

The proportion of clay-grade particles in a deposit varies depending upon how the deposit was formed. Most argillaceous sediments contain a considerable quantity of much coarser particles or clasts, either fragments of the original parent rock from which the deposit weathered or particles accumulated as the materials were moved by wind or water action. The term clay is reserved in analyses of consolidated (rock) and unconsolidated (soil) sediments for materials in which the clay particle size grade predominates. Mudrocks, for example, usually form at the end point of transport of the finest sediments, especially in oceans and lakes (Potter et al. 2005; Tucker 2001). In these rocks, as in other deposits of clay-sized particles, 10–20% or more of the composition may be of non-clay minerals (Velde 2010a: 10).

In analyses of soils, the relative mixture of clay-grade particles with larger particle sizes forms the basis of descriptive categories such as clay loam, silty clay, and so forth (fig. 2.3). To be designated a clay by pedologists (see, e.g., Liu and Evett 2008), the sediment must carry at least 35% particles smaller than 0.002 mm according to some classifications; by other schemes this fraction must be not less than 40%. Silty clay sediments contain 80–100% of their composition as silt-sized (0.05–0.002 mm) and clay-sized particles in approximately equal proportions.

The distribution of clays, silty clays, and clay loams in a region typically may be found on soil maps plotted by pedologists or agronomists. In most cases, however, the scale of these maps is not sufficiently fine to pinpoint the precise location of clays suitable for pottery, and in many areas modern construction precludes access to particular deposits. Nonetheless, the maps give a general picture of the kinds of soils in an area and the locales with some potential for yielding clayey resources.

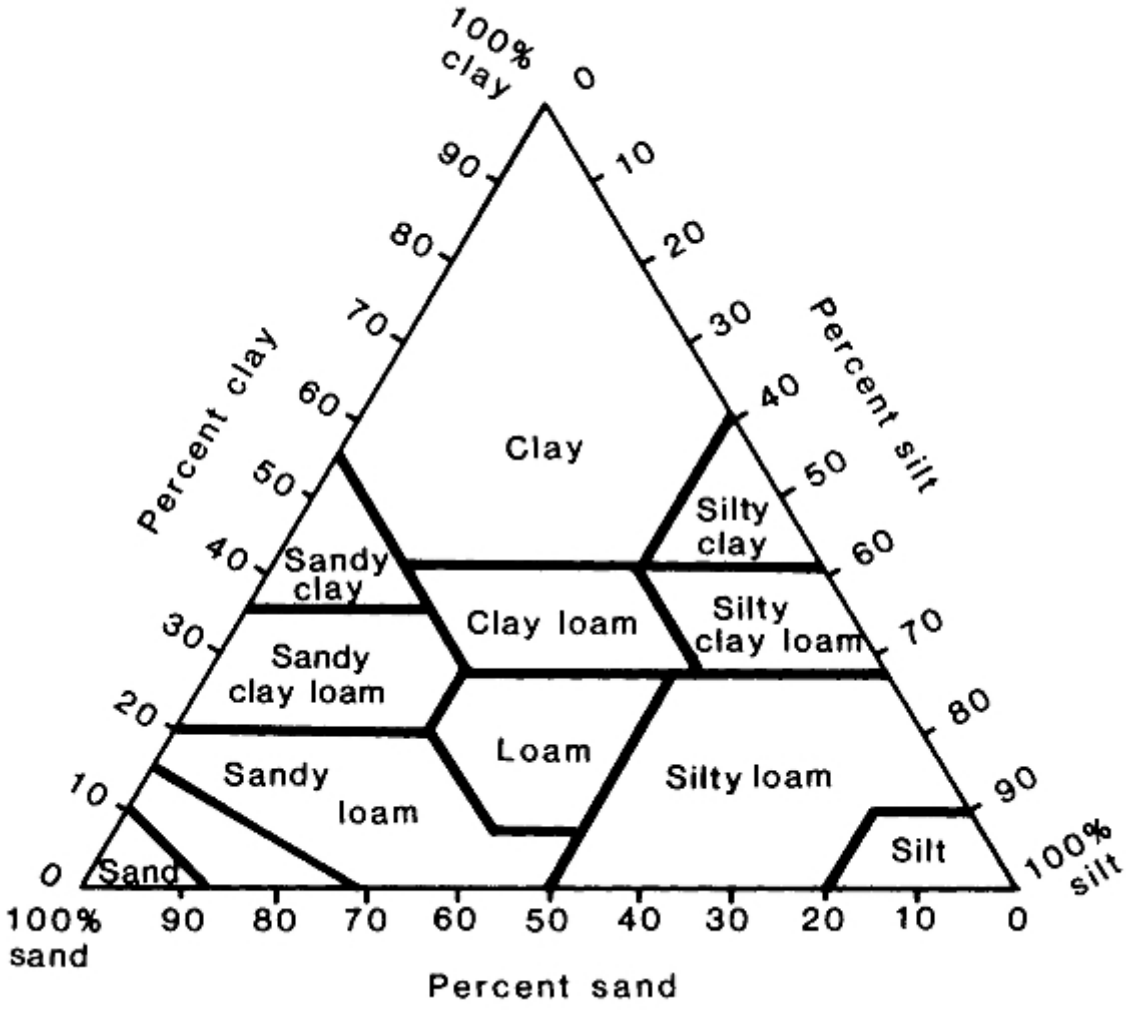

Figure 2.3 Ternary diagram of soils classification by particle size.

Fine-textured plastic clays are apt to be found as deposits in shallow, quiet lakes, slow-flowing streams, or estuaries, although some glacial clays may contain a variety of non-clay minerals in extremely small particle sizes. Hydrothermal clays, which are formed by alteration through contact with hot (100–300°C), often acid, mineralized solutions, may have as little as 5% coarse particles (Grim 1968: 2). But for a soil material to exhibit plasticity, that essential characteristic of clays, it may contain as little as 15% of the fine particle-size range.

2.2.2 Depositional Situation

Clays are sedimentary deposits that, in geological age, are comparatively recent accumulations of the products of weathering and disintegration of much older rocks. The depositional situation of clays—that is, the location of the decomposed material relative to the parent rock—is one basis for classifying clay deposits and understanding their properties.

Clay deposits remaining in more or less the same location as the parent material from which they weathered are variously called primary or residual (or authigenic in special circumstances) clays. They develop through a series of hydrolytic reactions involving percolation of groundwater and chemical action, plus other weathering factors (such as freezing). Residual clays form from many different kinds of rock, including felsic, granite, basalt, diorite, and volcanic ash or tuff. Even if the parent rock is sedimentary (e.g., limestone or shale), the clay is still a primary clay if it is located near that source. In the case of limestones, clays are usually present as weathering products in the initial sediment during or before consolidation of the rock. They remain after these processes and agents, especially acidic solutions, have leached away the calcareous and carbonaceous material.

Because the alteration and disintegration of the parent rock, whatever its composition, are not always complete, residual clays frequently contain coarse, unaltered, angular fragments of this material. These minerals, which may constitute as much as 90% of the deposit, most commonly include quartz, feldspar, mica, and pyrite. Primary clays usually have a low organic content (less than 1%) and are often coarse and of low plasticity.

Clays found in deposits or beds some distance from a probable parent source are variously called secondary, transported, or sedimentary (less often detrital or allogenic) clays. They were moved some distance from the parent rock or soil by wind, erosion, waves, tides, streams, glaciation, or other forces. More abundant than primary clays, transported clays may represent more than 90% of clay mineral deposits (Hillier 2010: 165–66). They also may be more homogeneous and finer in texture, as a result of sorting and redeposition, and often have a relatively high organic content of 5–10%, which varies with depositional context.

Secondary clays may be further categorized by the conditions or methods of transport and deposition, as fluviatile, lacustrine, aeolian, glacial, or marine clays (Hillier 2010: 169–77). Lacustrine clays may occur in lenticular deposits, decreasing in fineness near the edges; they are often high in organic matter. Glacial clays are generally coarse and unsorted, high in impurities, and useful for structural products or earthenwares.

Marine clays are probably the largest sedimentary clay deposits, formed when extremely fine clay particles in rivers were carried to their ultimate destination and settled out after contact with and adsorption of the ions in brackish seawater. Marine clays may be subdivided into fine pelagic or deep-water deposits, and coarse, organic-rich littoral (deposited between high- and low-water marks) and estuarine (principally for structural products) clays. Studies of in situ changes (diagenesis) in the clay minerals in marine deposits as well as the formation of clays at deep sea hydrothermal vents have contributed to something of a renaissance in clay mineralogy studies, as they appear to be linked to petroleum generation (Moore and Reynolds 1997: 4, 187).

2.2.3 Chemical Composition

Another useful way to define and describe clays is by their chemical composition. Ceramic materials combine a metallic element with a nonmetal or metalloid. Chemically, a metal is an element that has few electrons in its outer orbit, gives them up easily (that is, it tends to form cations), and combines with oxygen to form basic oxides. Nonmetals gain or share electrons and form acidic oxides. Metalloids have properties of both metals and nonmetals. Because clays are the end products of weathering of silicate rocks, most are primarily composed of aluminum and silicon, the two elements most resistant to weathering. Aluminum is a metal: in clays it is present as alumina or aluminum oxide (Al_2O_3), which gives up electrons, and combines with the metalloid silicon, present as silica or silicon dioxide (SiO_2), which may add or share electrons.

Table 2.4 Ideal Chemical Formulas of the Clay Minerals

Kaolinite	$Al_2(Si_2O_5)\ (OH)_4$
Halloysite	$Al_2(Si_2O_5)\ (OH)_4 \cdot 2H_2O$
Montmorillonite	$\left(Al_{1.67}\ Na_{0.33}\ Mg_{0.33}\right)(Si_2O_5)_2\ (OH)_2$
Illite	$Al_{2-x}Mg_xK_{1-x-y}(Si_{1.5-y}Al_{0.5+y}O_5)_2\ (OH)_2$
Mica	$Al_2K(Si_{1.5}Al_{0.5}O_5)_2\ (OH)_2$

Source: After Kingery et al. 1976: 7.

Most clays may be described more specifically as hydrous aluminosilicates, having three essential components—water, alumina, and silica. They are variants of the general or theoretical formula $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$ (table 2.4), the average composition of silicate clays being 39.4% alumina, 46.6% silica, and 13.91% water. The actual percentages of these components vary considerably in nature because different kinds of clays or clay minerals vary in atomic structure. Thus the ratio of silica to alumina may range from 1:1 to 4:1 or higher, and water may constitute as much as 30–35% of the clay body.

The edges of clay particles are unsatisfied electrically, so they tend to bond readily with other elements. Thus iron, calcium, sodium, and magnesium not only may substitute within the atomic structure of different clays, but also may bond to the particles as impurities in the form of oxides of soluble salts to satisfy electrical charge requirements. This bonding tendency, along with these attached elements and compounds themselves, plus carbon compounds, accounts for the common minor or trace elemental constituents present in clays. These elements play important roles in individual clays' behavior, such as their working properties and fired characteristics, including their fired color.

Besides the silicate clays, another chemical group consists of the hydrous oxide clays. These are particularly associated with acid weathering (leaching) or laterization of soluble components in tropical regions, in which silica is removed and insoluble iron and aluminum remain. Because these clays represent the most advanced or end stage of alteration of soil/rock material, they are very stable. Generally red or yellow in color, hydrous oxide clays may be intermixed with silicate clays and are represented by the formulas $Fe_2O_3 \cdot xH_2O$ and $Al_2O_3 \cdot xH_2O$ (the amount of water of hydration in these clays is variable).

2.2.4 Mineralogy: Phyllosilicates

Despite millennia of clay usage, the knowledge that clays are actually minerals was achieved only recently. For a long time clays were considered to be amorphous (noncrystalline), colloid-sized grains invisible to the naked eye. Variations in the properties of clays and soils were believed to be a consequence of impurities (Ashley 1909; Grim 1968: 13–18). Beginning in the 1920s, improved techniques such as X-ray diffraction (Rinne 1924) and optical petrography (Ross and Kerr 1931a) revealed that clays are extremely fine crystalline solids rather than amorphous materials, with definite internal structures and arrangements of atoms. The internal structure in most clays originates in their layered sheets of silica tetrahedra and alumina octahedra (although not all clays have this structure). This layering means that most clays have a flat lamellar or platelet shape, with a ratio of thickness to diameter on the order of 1:12. By the early 1930s the clay-mineral concept was firmly established, following several seminal publications (e.g., Ries 1927; Ross 1928).

Box 2.1 The Chemical Structure of Clay

Because many properties of clays that are critical to pottery manufacture and function result from their chemical composition and structure (Newman 1987a), a general understanding of clay chemistry and geochemistry is important. This understanding can be developed in several steps:

First, it is convenient to think of clays as composed of two kinds of "building blocks." Each block is an arrangement of two of the three chemical components of clays: one building block is silica, consisting of atoms of silicon (Si) combined with oxygen (O); the other block is alumina, consisting of atoms of aluminum (Al) with several oxygens or hydroxyls (OH).

Second, a basic understanding of atoms and electrical charges is needed. Elements are composed of atoms, which have two parts, a nucleus and an electron distribution; each is electrically charged. The nucleus comprises positively charged protons and uncharged neutrons that together give the nucleus a net positive electrical charge. Electrons revolve around the nucleus in nested orbits (or shells, energy levels) and have negative charges. Atoms possess equal numbers of protons and electrons and are electrically neutral.

Atoms of one element may combine, or bond, with atoms of another element by gaining, losing, or sharing electrons in their outer shells. If one or more electrons is gained, the atom then possesses more electrons (negatively charged) than protons (positively charged), resulting in a net negative charge; it is called an anion (−). Conversely, if electrons are lost, the atom has fewer electrons than protons and is a cation (+) with a net positive charge. Metallic elements form cations.

Because the transition from a neutral atom to a positive ion (cation) involves losing electrons, the effective size (ionic radius; table 3.1) of a cation is reduced compared with that of a neutral atom of the same element. Conversely, the formation of a negative ion involves filling this outermost shell, and thus anions enlarge compared with neutral atoms. In general, then, anions are usually found as relatively large nonmetallic elements, and cations as smaller metallic (alkali or alkali earth) elements.

The creation of positively and negatively charged ions by the sharing of electrons between atoms produces stable chemical compounds—combinations of one or more elements in definite proportions. This process of combination often occurs when large anions are arranged in a close-packed structure, with the smaller cations fitting into the spaces between them. The number of electrons in question is noted as a superscript: for example, one electron is involved with Na^{+} and K^{+} cations and Cl^{-} anions, two with magnesium (Mg^{2+}), and three with aluminum (Al^{3+}).

Third—to return to matters of clay and the structure of clay particles specifically—the elements aluminum and silicon are both cations (i.e., small and positively charged). Aluminum must lose three electrons to attain chemical and electrical stability (as Al^{3+}), and silicon must lose four to become Si^{4+}. In clays, both these cations lose their electrons to oxygen atoms, each of which needs two electrons to complete its outer shell and become O^{2-}.

And, fourth—to return to the first point of this discussion, the concept of "building blocks"—the form and arrangement of the silicon and aluminum cations with the oxygen (or hydroxyl) anions is distinctive in clays. They form sheet-like arrangements, as follows:

Silicon combines with oxygen to form a tetrahedron consisting of the small central silicon cation surrounded by four larger oxygen atoms equally spaced around it (fig. 2.4*a*). This silicon-oxygen tetrahedron, a strong anion, is the basic constituent of all silicate rocks. In clays these tetrahedra typically join together in a single plane by sharing oxygen atoms at their "corners." This occurs because in the transfer of four silicon electrons to four oxygen atoms, the oxygen atoms' electrical charge requirements are not satisfied, given that four oxygens require eight electrons to become O^{2-} ions. To achieve charge completion, the oxygens in one tetrahedron bind with four oxygens at the

bases of five additional tetrahedra, forming hexagonal rings of tetrahedra (fig. 2.4*b,c*). This process repeats indefinitely, forming a sheet-like arrangement of hexagons.

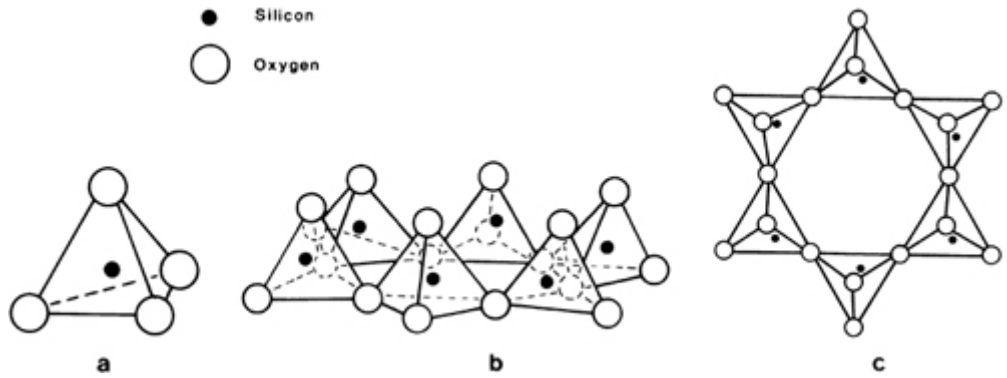

Figure 2.4 The configuration of silica: *a*, tetrahedral arrangement of silicon and oxygen; *b*, *c*, the hexagonal arrangement of silica tetrahedra.

Similarly, aluminum cations form octahedra with two oxygens and four hydroxyls equidistantly spaced around the aluminum (fig. 2.5). Because aluminum is tervalent, giving only half a charge to each of the six other particles, it is still electrically unsatisfied. Thus, alumina octahedra join to each other in a sheet by sharing the corner oxygens and hydroxyls, as do the silica tetrahedra. Typically three sites in the octahedral sheet are unfilled, and the number of cations—two or three—required to fill them determines whether the mineral structure is dioctahedral or trioctahedral, respectively.

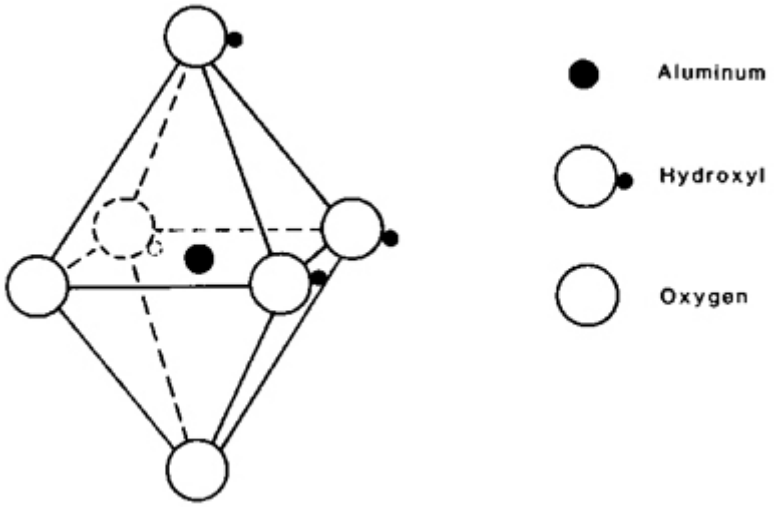

Figure 2.5 The octahedral arrangement of aluminum, oxygen, and hydroxyls.

Fifth and finally, then, the way the sheets are put together ("sandwiched") in a mineral is called the "layer type." A single sheet of silica tetrahedra combined with a single sheet of alumina octahedra has a 1:1 layer type; two sheets of tetrahedra with an alumina sheet in between has a 2:1 layer type. The stacking of these layers, which are weakly bound to each other by the shared oxygen layers, along with any interlayer material (frequently water), is known as the mineral's unit structure. This flat unit structure, with generally weakly bonded layers, results in the lamellar, platelet shape of the particles of many clays.

This configuration is the theoretical or compositional ideal structure of a "pure" silicate clay. It is frequently confounded, however, because silicon and aluminum, the cations of these tetra- and

octahedral arrangements, can be replaced by other elements to varying degrees. For example, Mg^{2+}, Fe^{2+}, or Fe^{3+} may substitute for Al^{3+}, or Al^{3+} may substitute for Si^{4+} owing to satisfaction of electrical charge requirements or size similarities (ionic radii). These cations then "fit" between the oxygens and hydroxyls. It is this compositional complexity that gives rise to the many different kinds of clays.

After World War II, with significant advances in analytical instrumentation, interest in clay mineralogy expanded throughout Europe and North America (for histories, see Brindley et al. 1951; Grim 1939, 1950, 1965, 1988; Grimshaw 1971; Hendricks 1942; Moore and Reynolds 1997: 14–17). It became clear that many kinds of clay minerals existed, but efforts to develop a satisfactory taxonomy proved extraordinarily difficult, with disagreement even about appropriate criteria, although crystalline structure and properties (shape, expandability) were most commonly used. Classification was also complicated because of overlapping characteristics: some clay minerals appeared to have properties intermediate between one category and another, a consequence of weathering processes and diagenesis. National and international committees (e.g., AIPEA, Association Internationale por L'Etude des Argiles) formed to discuss issues of taxonomy continue to be active as terminological precision and distinctions among and between minerals still are not completely resolved (e.g., Guggenheim et al. 2006, 2009; Martin et al. 1991).

Table 2.5 Classification of the Major Clay Minerals

- I. Planar phyllosilicates (sheet structure)
  - A. Two-layer (1:1) clays
    - 1. Kaolin group
      - a. Kaolinite
      - b. Nacrite
      - c. Dickite
    - 2. Halloysite group
  - B. Three-layer (2:1) clays
    - 1. Smectite group
      - a. Montmorillonite
      - b. Beidellite
      - c. Saponite
      - d. Nontronite
      - e. Sauconite
    - 2. Illite group
      - a. Illite
      - b. Glauconite
    - 3. Other groups
      - a. Chlorite
      - b. Vermiculite
- II. Non-planar phyllosilicates (lath or chain structure)
  - A. Attapulgite, palygorskite
  - B. Sepiolite

Source: After Moore and Reynolds 1997: table 4.3.

Today's clay mineral classifications are based on a combination of structural (type of silicate layering) and chemical (interlayer and electrical charge) characteristics. The most common clay minerals are hydrous layer silicates or phyllosilicates (Gk. *phyllon,* leaf), specifically planar hydrous phyllosilicates (Guggenheim and Martin 1995: 256; Martin et al. 1991). Phyllosilicates exhibit two arrangements of the silica tetrahedra and alumina octahedra structural components or building blocks (table 2.5). The 1:1 layer type comprises a relatively small group of clay minerals and is exemplified by kaolinite, whereas the large 2:1 layer type of phyllosilicates includes several mineral groups and their individual clay species (or named minerals). A secondary variable in classifications is the mineral's "octahedral character" based on the cation-to-anion ratio, or the numbers of spaces that need to be filled to satisfy the electrical charges of the hydroxyls in the octahedral layer (see Bailey 1980; Martin et al. 1991).

Not all phyllosilicates are clays in the senses of either granulometry or plasticity, although they may be closely related structurally. Examples of non-clay phyllosilicates include familiar minerals such as serpentine, talc (steatite), and mica (Martin et al. 1991). In addition, not all clay minerals are characterized by a layered structure: some have a chain or lath type of structure, and a small group of non-crystalline minerals (allophane) are amorphous to X-ray diffraction, making them difficult to analyze.

Attention here is given principally to the phyllosilicate clays. Table 2.6 summarizes some important properties of clays.

Table 2.6 Properties of Some Clay Minerals

Property	Kaolinite	Smectites (Montmorillonite)	Illite	Chlorites, Hydrous Micas
Occurrence	Highly weathered, especially by acid leaching; widespread; occurs as primary and secondary clays	Not heavily weathered; especially characteristic of arid and alkaline environments	Especially in marine and calcareous sediments	Commonly mixed with other clays
Type	Two-layer	Three-layer expanding	Three-layer nonexpanding	Mixed layer
Particle size and shape	Relatively large hexagonal plates, 0.3 μm–0.01 mm diameter	Very small and poorly defined; much less than 1 μm diameter	Small, thick, poorly defined	Variable and poorly defined
Plasticity	Sedimentary—good; residual—low	Very good	Good	Poor
Shrinkage	Low	High	. . .	. . .
Fired color	Sedimentary—sometimes white; residual—variable	Variable—cream, red, light brown	Variable	Brown, red, black
Refractoriness	High, 1710°C	Moderate 1350–1450°C	Low, 1000–1300°C	Low to moderate, 1200–1500°C
Other	Sometimes has natural luster	High base exchange, high absorption, low luster	Natural luster, good for slips	. . .

2.2.4.1 Planar Phyllosilicates

Kaolin Group. Clays of the kaolin group are composed principally of the clay mineral kaolinite. The name kaolin is believed to come from *kao lin* or *kau ling* ("high hill"), designating a locale near Dazhou in Kiangsi Province, China, where white clay for porcelain was obtained (see Chen et al. 1997). The use of the term began in 1867.

Kaolinite has a 1:1 or two-layer structure consisting of two sheets, one of silica tetrahedra and one of alumina octahedra (fig. 2.6; Brindley and Robinson 1946; Gruner 1932; Ross and Kerr 1931b). Particles are usually flat hexagonal plates (fig. 2.7) of moderate to large size, ranging in diameter from 0.3 μm to 0.01 mm and approximately 0.05 μm thick. The mineral is dioctahedral, meaning that two of every three points around the hydroxyl need to be filled with a cation. The vacancy of every third site causes some distortion or departure from the ideal fit of the layers, generally resulting in a thinning of the sheet (Moore and Reynolds 1997: 110–12). Nonetheless, the bond between the units is relatively strong, providing little opportunity for ion substitutions in

the structure—known as low base exchange or cation exchange capacity (CEC)—and thus the composition and properties of kaolinites are relatively constant. Besides kaolinite, other clay minerals of the kaolin group are halloysite, dickite, and nacrite (Moore and Reynolds 1997: 140–45).

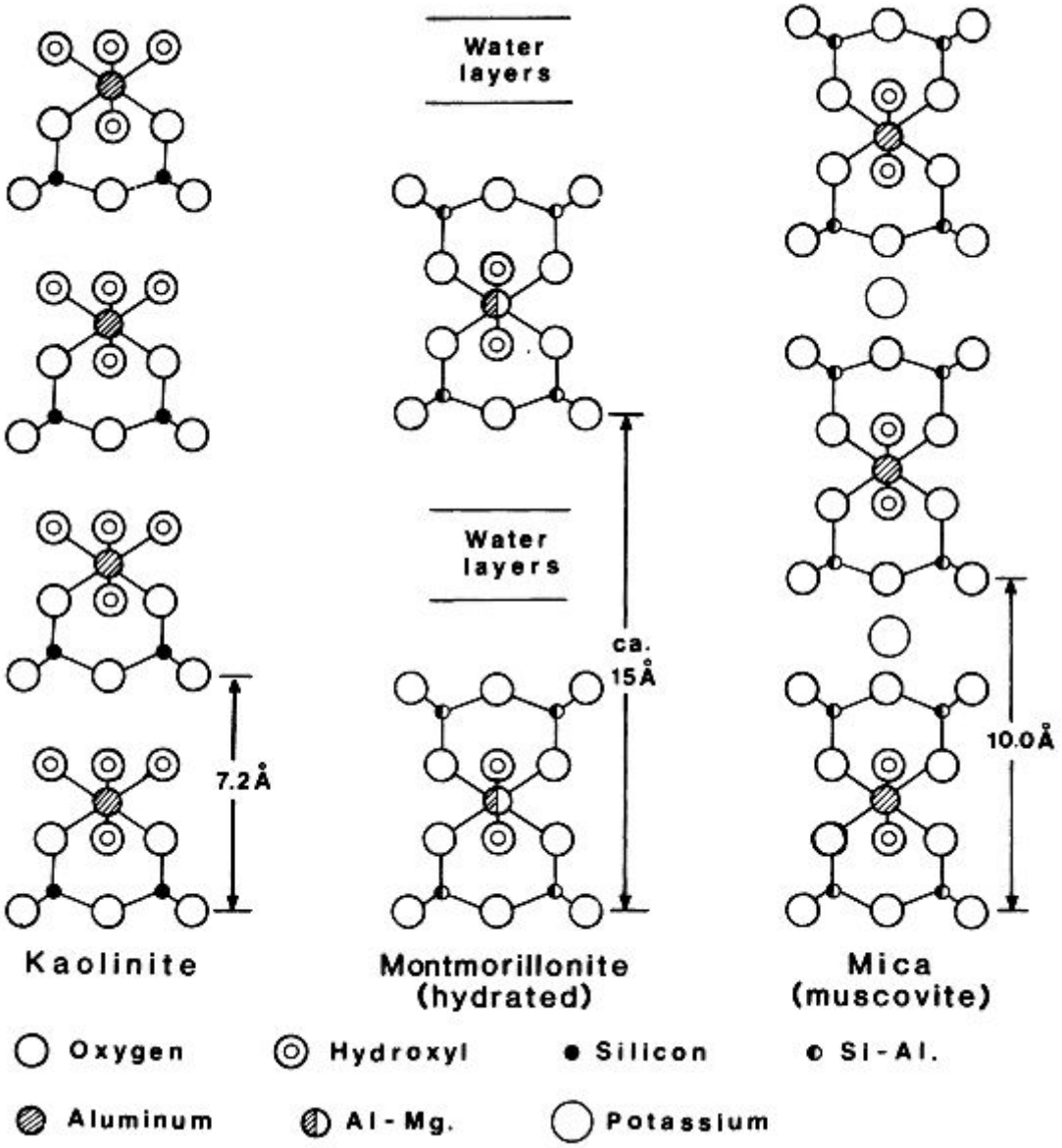

Figure 2.6 The layer structure of kaolinite, smectite (montmorillonite), and mica, showing the position of common cation substitutions, water layers, and average lattice constants (the distance between repeated layers). After Kingery et al. 1976: fig. 2.35.

Kaolinite represents an advanced stage of weathering of the parent material, usually a felsic rock such as granite or granitic pegmatite (coarse-grained igneous rocks high in feldspar and quartz) or micaceous schist (e.g., containing muscovite). The mineral is most often formed in warm tropical or subtropical regions with high rainfall and good soil drainage, resulting in acid leaching, which removes most elements—especially bases such as calcium, magnesium, iron, sodium, and potassium—other than silicon and

aluminum from the parent. Because of its 1:1 layering, kaolinite is generally high in alumina, which often exists in a ratio of two to one with silica. The mineral is described by the idealized formula $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$ and has an average chemical composition of 39.4% alumina, 46.6% silica, and 13.9% water. When weathering and leaching are extreme, especially in tropical equatorial regions, even more silica is removed, forming the hydrous oxide clays and deposits of the high-alumina minerals bauxite and gibbsite.

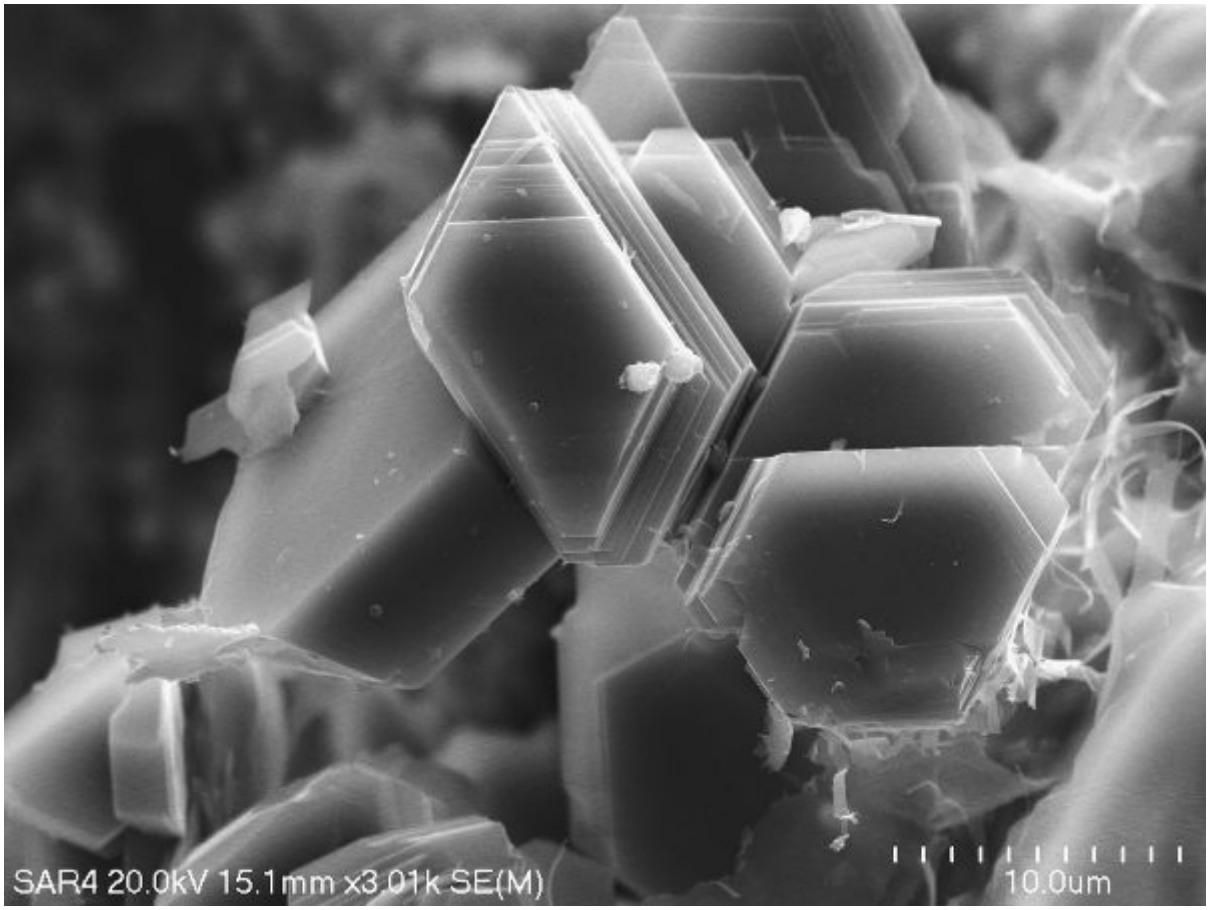

Figure 2.7 Hexagonal platelets of kaolinite. Image reproduced with the kind permission of the Clay Minerals Society and the Mineralogical Society of Great Britain & Ireland from the "Images of Clay" gallery available at www.minersoc.org.

Kaolin clays may exist as primary or secondary deposits, and they are widespread in temperate and tropical zones of Earth. Also, they (and other clay minerals) have been identified on Mars (Bishop et al. 2008). Residual kaolin clays are usually low in plasticity, coarse, and full of impurities, chiefly remnants of the parent rock including partially decomposed feldspar and unaltered rock minerals. Sedimentary kaolins usually benefit from sorting during transport and deposition, which makes them finer grained. Depending on the location of the deposit, however, the sediment may be highly organic (e.g., lacustrine deposits). In ancient sediments, kaolinite is abundant in clays of fluviatile origin and nearshore deposition. In more recent soils, kaolinite minerals are

common in red and gray, usually acidic, podsols and laterites. Alkaline or calcareous (e.g., limestone-derived) sediments tend not to include kaolinite, and calcium may inhibit the formation of the mineral (Grim 1968: 548).

Certain kinds of kaolin clays, primarily sedimentary deposits, are relatively free of fine impurities such as iron (see Bertolino et al. 2010) and other colorants, and fire to a white color. These white clays are comparatively uncommon and are accorded special value in both ancient times and modern industry. They are important for paper sizing (nearly one-third the weight of slick-paper magazines is kaolinite; Mason and Berry 1968: 443), vitreous plumbing fixtures, and tableware. Indeed, kaolin clays are often called china clays, although this term usually refers more specifically to primary kaolin deposits. Because of their high alumina content and resistance to absorbing impurities, china or white kaolin clays are typically refractory (they resist melting at low temperatures). Their comparatively large particle size, averaging 0.6 to 1.0 μm or more, makes them rather low in plasticity, and they also have a low drying shrinkage; products may attain a high natural luster without polishing. Among the white-firing kaolin deposits that are commercially significant today are the deep residual kaolins formed from hydrothermal alteration of granites in Cornwall, England, and the plastic, sedimentary kaolins along the southeastern Appalachian "fall line" in the Carolinas and Georgia, formed by erosion of kaolinized granite and subsequent transport and redeposition.

Halloysite, the second major mineral category in the two-layer group, may be a weathered or disordered form of kaolinite. It has some irregularity in the stacking of its silica and alumina layers, leading to more water in the structure and a tendency for its thin platelets to curve or roll into tubelike forms. Halloysite has been found to develop fairly rapidly from volcanic ash as recent as four thousand years old in tropical environments (Hay 1960). Halloysite, and also nacrite and dickite, tend to be formed by hydrothermal action.

Smectite Group. The smectite clay group is the largest of several hydrous phyllosilicates with a 2:1, or three-layer, structure (Moore and Reynolds 1997: 155–58; Odom 1984). Smectite was previously referred to as montmorillonite, the most common member of the group, named in 1948 after Montmorillon, France.

As with kaolins, smectite particles are thin and platy, but they do not exhibit the regular hexagonal shape of kaolinite crystals (fig. 2.8). In addition, the platelets are slightly thicker but considerably smaller than those of kaolinite, ranging from 0.05 μm to 1 μm in diameter. Because of this small particle size, smectite clays are usually very plastic and "sticky." Some smectite clay minerals (montmorillonite, beidellite; see Emmerich et al. 2009) are dioctahedral, whereas others (e.g., saponite) are trioctahedral.

The three-layer or 2:1 clays are composed of two sheets of silica on either side of a layer of alumina (see fig. 2.6). In both silica sheets, the tetrahedra are oriented with three corners outward and a single point directed inward toward the layer of alumina octahedra; in the alumina layer only two of the eight oxygen tips point outward, one to each flanking silica layer. Because chemical bonding occurs only at the oxygen tips, these bonds are loose. In addition, the hydroxyls remain unbonded and electrically unsatisfied, and only a weak bond exists between one three-layer silica-alumina-silica unit and the ones stacked next to it.

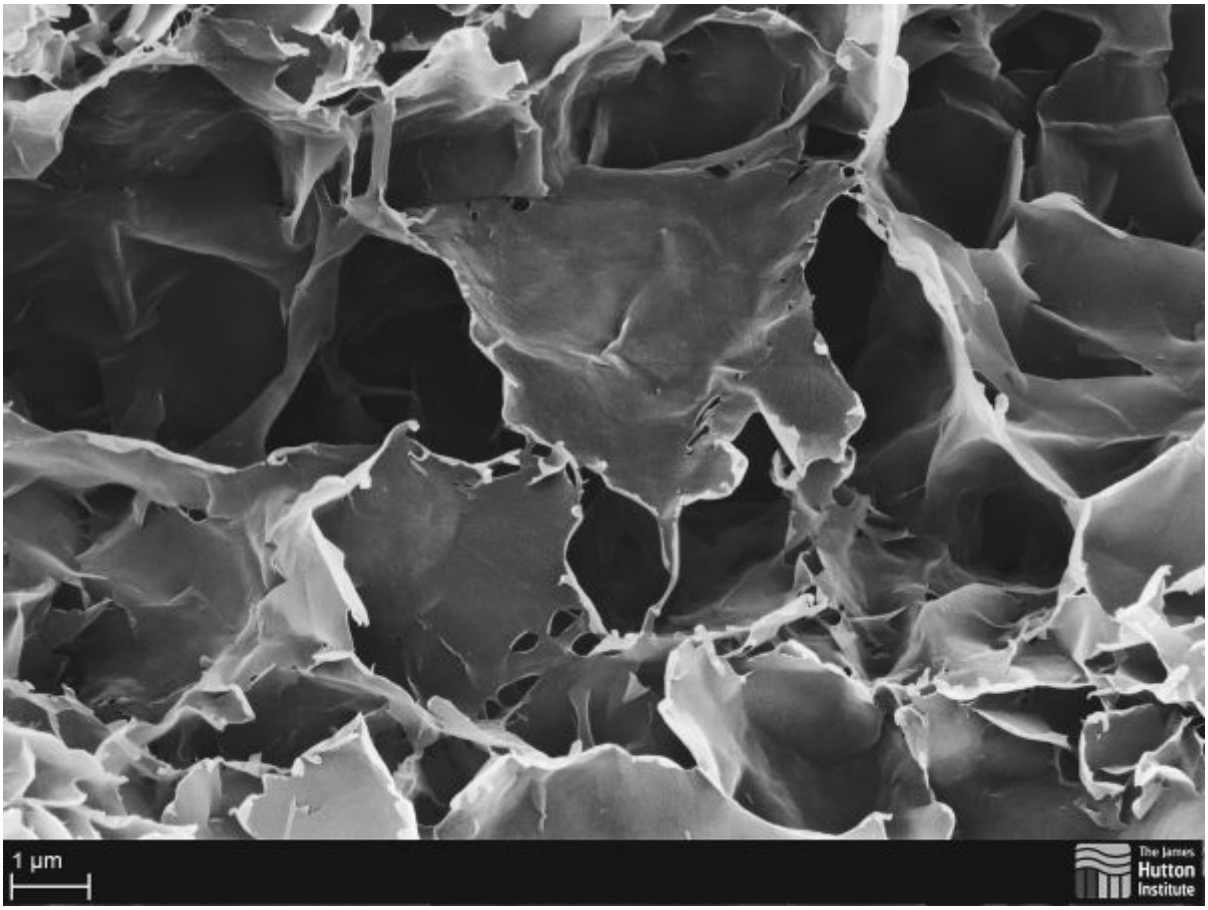

Figure 2.8 Particles of smectite (montmorillonite). Image reproduced with the kind permission of the Clay Minerals Society and the Mineralogical Society of Great Britain & Ireland from the "Images of Clay" gallery available at www.minersoc.org.

Smectite clays are formed chiefly by alteration of basic rocks and minerals high in calcium, magnesium, and iron, such as basalts and calcic plagioclases, or by decomposition of volcanic ash. They are formed under conditions of relatively poor drainage, reduction, low rainfall, and leaching, particularly when bases such as magnesium, iron, calcium, sodium, and potassium are relatively abundant in the zone of weathering. Smectites tend to be common in recent sediments: in the Amazon delta, for example, authigenic potassium- or iron-rich smectite may form by alteration of biogenic silica (diatoms) (Michalopoulos et al. 2000). Smectites also are major components of

soils in arid regions. These clays are not as highly weathered as kaolinites; in fact alteration—especially leaching with high rainfall, high temperature, and good drainage—will remove bases and so transform smectites into kaolinites.

The theoretical composition of smectite clays is 66.7% silica, 28.3% alumina, and 5% water. Thus in comparison to kaolin clays, smectites have a higher ratio of silica to alumina (on the order of four to one), and so are less refractory (i.e., they melt at lower temperatures) and more fusible. In addition, smectites generally have more of the alkali metal elements (lithium, sodium, potassium, rubidium, and cesium). But because of water adsorption and substitutions within the crystal structure—their high CEC—the theoretical formula of these minerals nearly always differs from the actual chemical composition. The most common substitutions for the major cations in the smectite group are Al^{3+} and P^{5+} for Si^{4+}, and Mg^{2+}, $Fe^{2+,3+}$, Zn^{2+}, Ni^{2+}, or Li^{+} for Al^{3+} (Grim 1968: 83). If these substitutions are extensive, the result is a completely different clay mineral. For example, replacement of Al^{3+} by Mg^{2+} yields saponite, and replacement by Fe^{3+} distinguishes nontronite. Substitution of Zn^{2+} for Al^{3+} underlies sauconite, and replacement of Si^{4+} by Al^{3+} yields beidellite.

Smectite clays' weakly bonded three-layer structure gives rise to many properties that are valuable in varied commercial applications. For example, water molecules and atoms of numerous elements can easily penetrate the spaces between the unit layers (fig. 2.6), expanding their structure—they were often referred to as expanding lattice clays—or making them separate, or simply adsorb additional ions, such as colorants, with ease (high CEC). In most of the smectite clays this expandability is invisible, but in bentonite, which weathers from volcanic ash, the volume swells to a degree visible to the naked eye. Bentonites are highly absorbent and are often used commercially as decolorizers, as cat litter, and as clarifiers and stabilizers in wine production.

In terms of these clays' behavior in pottery making, their fine particles and tendency to adsorb water between the layers means that they usually have high shrinkage, often cracking as they dry. Also, the fineness may give them the characteristics of colloids, and this plus their open lattice structure and high CEC makes them useful for paints or slips. Smectites generally do not attain high luster. (For the use of smectite clays in construction at Çatalhöyük, see Hodder 2012: 65–67.)

Illite Group. Another major group of 2:1, three-layer clays is the illite group, named for the state of Illinois. Illites have proven to be heterogeneous, complex, and difficult to define and classify since their original identification (Moore and Reynolds 1997: 149–53). For example, illite clay minerals have structures similar to those of well-crystallized micas (fig. 2.6; Bradley and Grim 1961), and they have been considered dioctahedral parts of a "true (flexible) mica" group of phyllosilicates (Martin et al. 1991).

Structurally similar to smectites, although more stable geologically, illites have about one-sixth of the silicon replaced by aluminum, leading to a charge deficiency that is balanced chiefly by potassium (K^+), but also by Ca^{2+}, Mg^{2+}, and H^+. This charge deficiency lies primarily in the outer silica layers of the unit structure and is therefore close to the surface, rather than in the interior alumina layer as in smectites. It is largely for this reason that the illite clays are nonexpanding. Illite mineral particles occur in small, poorly defined flakes similar to but thicker than smectites, with diameters ranging between 0.1 μm and 0.3 μm. Nonetheless their fineness and tendency to display a natural luster make them useful for pottery slips. Slips on two famous categories of archaeological pottery, Greek black-figure ware and Arretine/Samian ware, were manufactured from illite clays.

Illite clays are particularly characteristic of calcareous marine deposits, especially offshore and in deep water. In the latter, they are likely formed by diagenesis: microbial bio-reduction of iron in smectites (Kim 2012; Moore and Reynolds 1997: 169–86). These deposits are linked to the generation of petroleum, particularly in shales. Alternatively, some illite deposits may relate more directly to the weathering and deposition of various clay sediments. In other situations illites may alter to smectites over thousands of years (Santiago Buey et al. 1998).

Other Groups. Several other groups of 2:1 planar hydrous phyllosilicates may occur as clay minerals (i.e., fine-grained and contributing plasticity) but they are typically secondary constituents along with the major clays associated with ceramics. These include the chlorite and vermiculite groups.

The chlorite clays (Brindley 1961; Moore and Reynolds 1997: 162–67), named around 1800, are primarily trioctahedral minerals colored light green by ferrous iron (Fe^{2+}). Chlorites (Gk. *chloros,* green) are commonly found in greenish schists and shales. A number of variants within this group arise from partial substitution of Fe^{2+} and Mn^{2+} for Mg^{2+} and from Fe^{2+} or Cr^{3+} partially replacing Al^{3+}. Chlorites are highly susceptible to weathering, are commonly mixed in small amounts with other clay minerals, and are often difficult to identify.

Vermiculite (Walker 1961) was named in 1824 from the Latin *vermiculus,* "worm," because vermiculite particles, when heated, look like small worms. Vermiculites are similar to smectites in having an expanding lattice, but their expansion is less. This may be partly because vermiculites occur in larger particle sizes, and there is less randomness in the ordering of the layers of the particles (Grim 1968: 111). Because they expand to become light and porous, vermiculite clays are useful in industry as insulation material and as fillers in concrete.

2.2.4.2 Non-planar Phyllosilicates

Two groups of 2:1 clay minerals have a fibrous, lath-like, or ribbon-like structure and a chain rather than sheet arrangement (Moore and Reynolds 1997: 167–68). The octahedra lack a continuous sheet structure and contain aluminum, magnesium, or iron cations surrounded by oxygens and hydroxyls. Relatively rare, they frequently occur mixed with other clay minerals as well as in calcareous material, and are easily destroyed by acid solutions, making them difficult to isolate and study. These minerals are typically associated with arid and desert regions, especially in tropical and semitropical latitudes, and they are also weathering products of basalts.

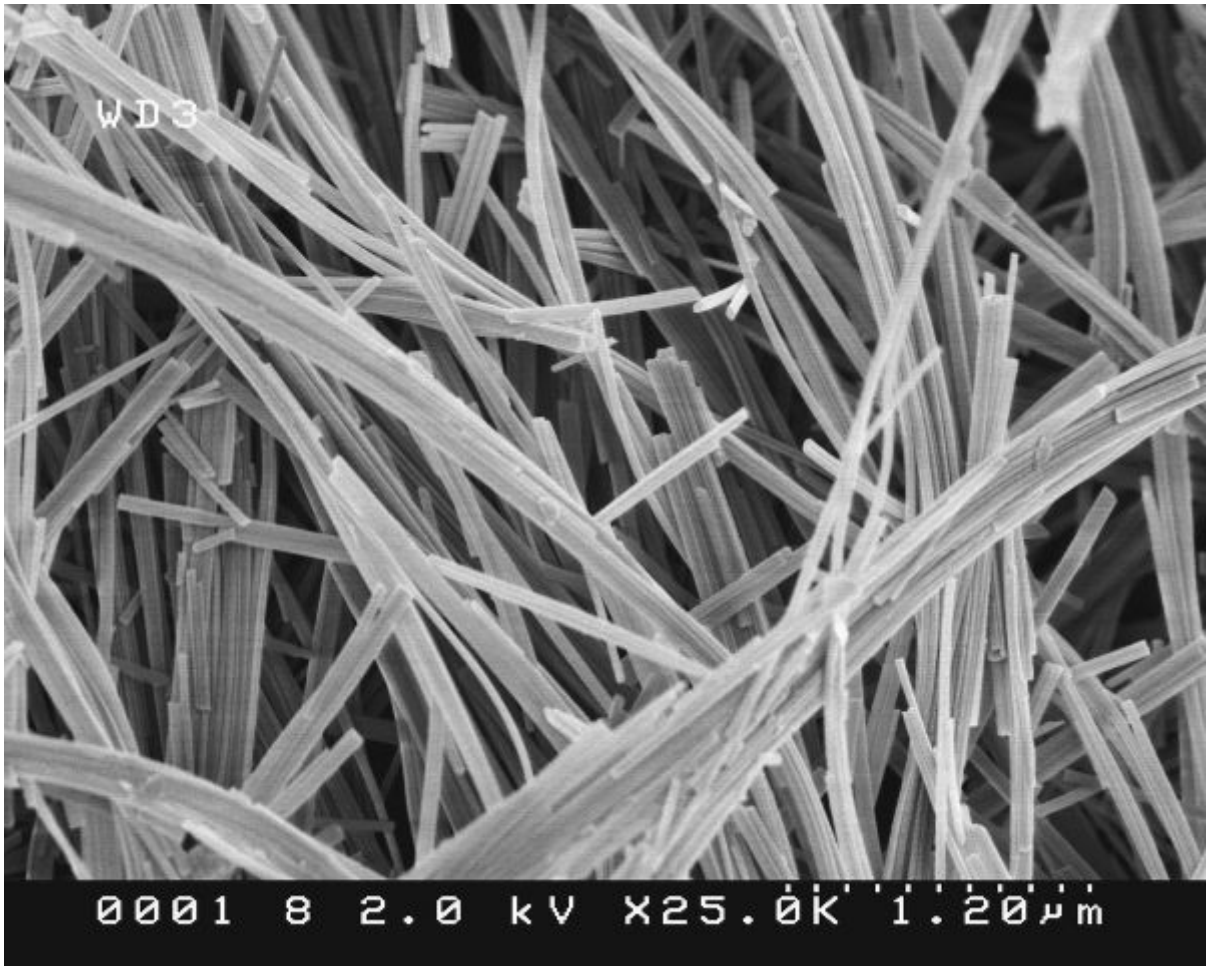

Figure 2.9 Laths of palygorskite. Image reproduced with the kind permission of the Clay Minerals Society and the Mineralogical Society of Great Britain & Ireland from the "Images of Clay" gallery available at www.minersoc.org.

The minerals of the chain phyllosilicates fall into two groups, the palygorskite (attapulgite) group and the sepiolite group (Galán 1996). Palygorskite and attapulgite clays occur as laths and bundles of laths, usually less than 5 µm long and often bent and tangled (fig. 2.9). Attapulgite, also known as fuller's earth, was identified in 1935 in Attapulgus, southern Georgia. These clays are highly absorbent and are used commercially as decolorants as well as ingredients in pharmaceuticals—for example, in antidiarrheal preparations. The two names are roughly synonymous, although there may be a tendency for palygorskite to be used in mineral studies and attapulgite to be

used for health applications. Palygorskite/attapulgite, bound with indigo, was identified by X-ray diffraction as the major component of the beautiful and much-studied ancient pigment called "Maya Blue" (Arnold et al. 2008; Cecil and Neff 2010; Doménech et al. 2009, 2014; Gettens 1961; José-Yacamán et al. 1996; Littman 1980, 1982; Shepard 1962b; Shepard and Pollock 1977; van Olphen 1966).

Sepiolite, named in 1847 (Gk. *sepion*, cuttlebone or cuttlefish), was often equated with meerschaum, the light-colored and -weight material used to make tobacco pipe bowls. Sepiolite occurs in laths that are thicker, shorter, and more densely packed than those of attapulgite.

2.2.5 Commercial Uses

Clays may also be categorized by their modern industrial or commercial uses, which cut across classes based on mineralogy and depositional context. Clays are mined and used for a staggering variety of products and purposes beyond their well-known functions as tableware and plumbing fixtures. Additional uses of clays and ceramic materials include dry cleaning agents, drilling lubricants, linings for hazardous waste disposal, and porcelain hand grenades. The major commercial categories are ball clays, fire clays, refractory clays, and heavy clay products (or structural) clays. Additional uses and descriptive terms, including stoneware clays, china clays, and flint clays, are common in the literature (see Grimshaw 1971: 290–311; Hopper 2009: 70–71; Moore and Reynolds 1997: 141–44).

Ball clays are important in the manufacture of whitewares, which include tableware, tiles, and sanitary ware. These clays are composed principally of the clay mineral kaolinite, although some may contain smectites and illites. Ball clays are commonly composed of 40–60% silica and 30% alumina, plus significant amounts (5% or more) of organic material and soluble salts. They are fine textured, highly plastic, secondary clays, often water transported and deposited in lakes or swamps, and they fire to a white or cream color. Ball clays usually have fairly high drying shrinkage yet are strong when dried but unfired (Holdridge 1956), a property called green strength. Ball clays typically are not used alone but are added to a mixture, such as that of porcelain, to improve its working properties.

Fire clays, a type of refractory clay found under coal deposits, are particularly useful for products such as furnace linings, high-temperature brick, and other industrial products that must withstand high temperatures. They are usually residual kaolinites that are high in alumina—more than 30% in most cases—and low in the alkali impurities that lower the melting and vitrification points. Refractory clays have a melting point above 1,600°C.

A third important use category is "building clay" or "heavy clay products clay," used for structural products such as bricks, roof tiles, and sewer pipes. These clays are generally red firing, as a consequence of an iron content of 3–8%, and they may be high

in impurities such as calcium and magnesium. Usually coarse textured and variable in plasticity, structural clays occur in poorly sorted primary and secondary deposits, including fluviatile and glacial clays and surface clay soils.

2.3 Functional Definitions

For anthropologists and archaeologists studying pottery, these details of depositional context, particle size, chemical structure, and mineralogical composition are essential to understand in some ways, but in other senses they are of less importance. The significance of the different viewpoints depends on the questions being asked. Chemical or mineralogical data about clays are not useful unless research questions are framed so that chemistry and mineralogy can provide answers.

To answer the crucial question, What is a clay?, it is helpful to consider contemporary traditional potters who produce their wares under relatively modest conditions, frequently without a wheel or kiln. Although these potters often exhibit considerable knowledge in selecting their materials and modifying them for use, their requirements for a usable clay are much less rigorous than those of modern industry. For the most part, traditional potters must choose from what is available. They may be selective when a wide spectrum of resources is present, recognizing special and desirable properties, but their criteria and limitations are not those of twentieth-century Western science and industry.

In addition, most noncommercial clays are not "pure" in either a monomineralic or a granulometric sense: they may be surface clay soils; they often consist of a mixture of interbedded clay minerals; and they do not have all the coarse, non-clay materials removed from them. Traditional village potters have several ways to increase the fineness of their clays, such as crushing, sifting, or levigation, and so did ancient potters. In general, however, these materials contain various substances besides clay minerals and clay-sized particles.

Furthermore, firing may eliminate the water ("hydrous") component of clays, destroying their crystal structure and rendering them mineralogically unidentifiable. Although this is more likely with pottery fired for long periods at high temperatures than with brief low-temperature bonfire firings, archaeologists studying ancient potsherds may find ceramic technological research futile if questions are based solely on clay mineral identifications.

The varied definitions of clays illustrate why archaeologists and anthropologists seeking assistance from geologists, mineralogists, or ceramic engineers to understand the properties of potters' resources should be aware of different approaches to the same topic. These scientists may define what is or is not a clay on the basis of strict definitions of particle size, mineral composition, or potential for commercial use. They may be skeptical if asked to analyze a clay sample collected from an archaeological survey area.

Functionally, however, in terms of selection and use by potters in the ethnographic present, clays may be defined solely by their most salient property, plasticity. Plasticity is the fundamental operational criterion for identifying a clay for the purposes of

traditional potters and anthropologists, regardless of chemical, mineralogical, or particulate character. Because potters in antiquity could not choose resources strictly on the basis of their being smectite rather than kaolinite minerals, or being 0.5 μm in diameter rather than 1 μm, these technical distinctions were generally not of primary interest. The first concern in making clay vessels, then, is a material's plasticity or workability.

On the other hand, for some analytical purposes technical properties may be of the highest significance to anthropologists and archaeologists. Mineral composition, chemical composition, particle size, CEC, and such, determine the characteristics that *did* influence prehistoric potters' decisions: workability, shrinkage, strength, thermal shock resistance, luster, color development. Questions of how potters—and perhaps non-potting painters or others—might have manipulated such distinctive properties of "natural" clays and clay mixtures to their aesthetic and economic advantage are of considerable interest. These properties provide the basic limits of variability within which to investigate matters that intrigue anthropologists, such as resource selection, production, decoration, and function. So, whereas ancient and contemporary village potters may not knowingly choose smectite clays, they may preferentially select for some of the *properties* of smectite clays, such as absorption and plasticity.

The point is that chemical, mineralogical, or granulometric analyses should not be undertaken simply as pro forma descriptive techniques; rather, they should be conducted with a very clear idea of what kind of information they can and cannot provide about the pottery or resources of interest. It is not the composition itself, but the properties that composition confers that are of interest in the study of pottery, whether ancient or contemporary. In looking for answers, in ceramic study as in other areas of research, it is important not to lose sight of the questions.

3 Plasticity: The Clay/Water System

> Plasticity: The unique property held by clays which combines the strength of a solid with the fluidity of a liquid.
>
> Hamer and Hamer 2012: 268

Of the many characteristics of clays that are significant to potters, the most fundamental is its plasticity. The property of plasticity is grounded in the idea of a "clay/water system": a clay becomes plastic only with the presence of some amount of water, and loses plasticity with the loss of that water. This chapter looks at the nature of the clay/water relationship and at plasticity, referring almost exclusively (except where noted) to the layered or planar phyllosilicate clays.

3.1 Water, Dipoles, and Ions

Although the meaning of "water" is intuitively understood, several kinds of water play a role in the clay/water system. Two kinds of water—hydroxyls (crystal lattice water) and interlayer water (between the layers of three-layer clays)—are chemically combined and part of the chemical structure of clay minerals, which is why they are called hydrous phyllosilicates. This is not the water involved in plasticity, however. Instead, the water that brings about plasticity is water added to, and mechanically or physically combined with, a dry clay. This water is said to be adsorbed by the clay particles, or weakly bound only to their surfaces and edges, and is easily removed from the clay at low temperatures (Dal and Berden 1965; Moore and Reynolds 1997: 117–25; Newman 1987b; Norton and Johnson 1944).

Water molecules are made up of one oxygen anion (O^{2-}) and two cations of hydrogen (H^{+}) (fig. 3.1*a*). Because of a non-centrosymmetric charge distribution, the water molecule acts as if it had two charges, positive and negative, even though the net charge of the molecule is zero. One end of the molecule, the end with the two hydrogen ions, has a partial positive charge, and the other end with the oxygen ion has a partial negative charge. A molecule with this structure is called a dipole because it has two electrical charges, or poles, separated by some distance.

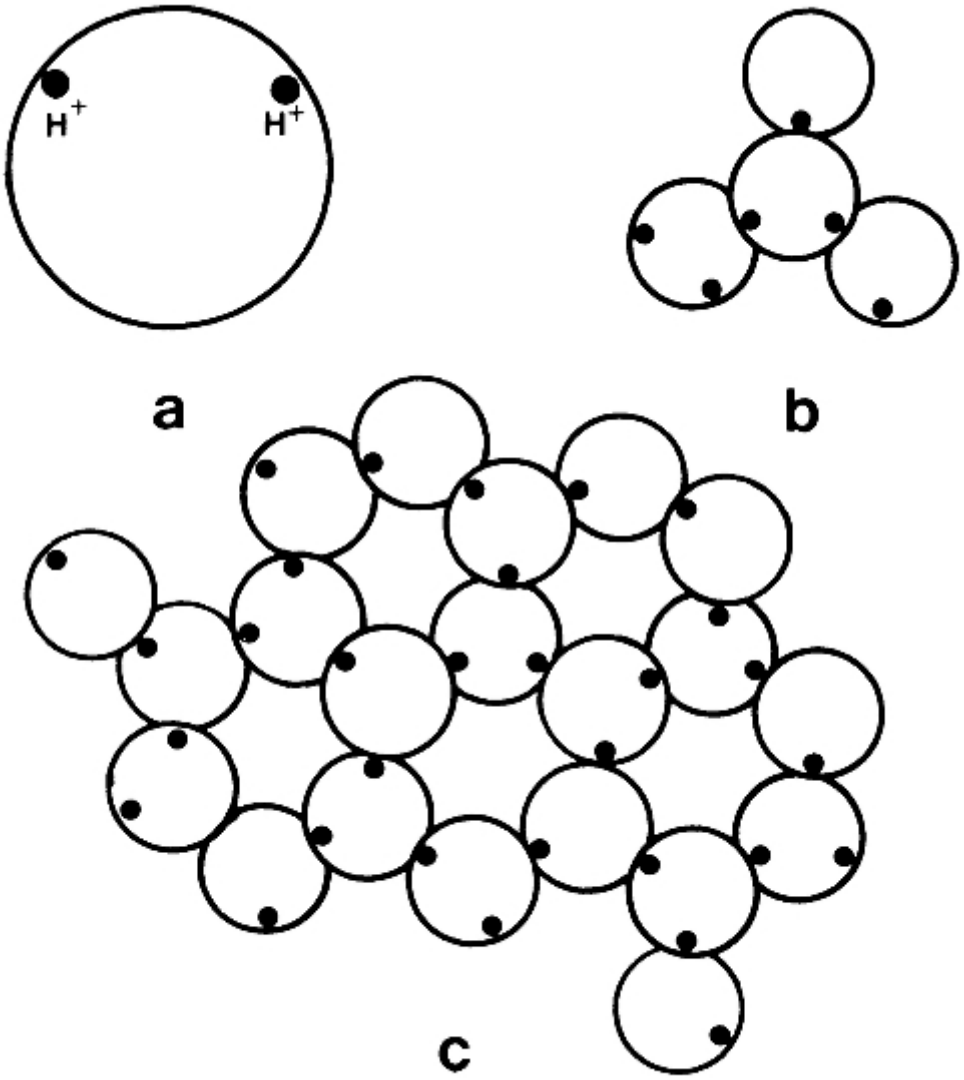

Figure 3.1 The structure of water: *a*, a single molecule, showing the dipolar structure resulting from the arrangement of two hydrogen nuclei; *b*, the tetrahedral arrangement of molecules; *c*, the hexagonal ring structure of water, formed by arrangements of tetrahedral, here shown in two dimensions. Sources: *a*, after Lawrence and West 1982: fig. 3–1; *b* and *c*, after Lawrence and West 1982: fig. 3–2*a*,*b*.

Dipolar molecules interact with other molecules and ions in two important ways. One is electrostatic attraction: their dipolar character (dipole moment) leads them to interact electrostatically with other dipolar molecules. A water molecule, for example, commonly associates with four other water molecules, the positive "ends" forming four ionic bonds with the negative "ends" of other molecules (fig. 3.1*b*), forming a hexagonal ring structure (fig. 3.1*c*). In some ways, then, the atomic structure of water molecules is similar to that of silica; the difference, of course, is that silica tetrahedra form two-dimensional sheets, whereas in water this hexagonal structure develops in multi-dimensions. The bonds holding the water molecules together are weak because the dipolar charges are only partial, reducing the electrostatic attraction. Further, the weak

dipole/dipole interaction is a strong function of distance and falls off rapidly with increasing separation.

A second key aspect of interactions resulting from the dipolar charge distribution concerns single ions. Ions with a positive charge (cations; e.g., Ca^{2+}) will be attracted to the negative end or side of water molecules, while ions with negative charges (anions; e.g., Cl^{-}) will be attracted to the positive side. The size of the ion is also important. Small ions such as Ca^{2+} or $A1^{3+}$, which fit into the center of the hexagonal water structure, will enhance its stability. Conversely, ions with radii larger than the size of the central area—greater than approximately one Ångström [Å] (or 1.0×10^{-8} cm, or 0.000,000,1 mm, or 0.1 nm), such as K^{+}—will disrupt the hexagonal arrangement (fig. 3.2).

These considerations are important because wet, plastic clays consist of individual platelet-like particles surrounded by films of water. Clay particles have active, electrically charged sites on their surfaces and edges that, depending on imperfections and the locations of broken bonds, result from the exposure of unsatisfied Al^{3+}, Si^{4+}, O^{2-}, and OH^{-} ions of the sheets of silica tetrahedra and alumina octahedra. Most generally, for example in kaolinite, the break is such that the surfaces of the platelets consist of O^{2-} or OH^{-} ions, whereas the edges are Al^{3+} or Si^{4+} ions. In other words, the edges of the particles have a positive charge and the surfaces a negative charge; clay particles thus have an overall negative charge (monopole), but with a dipole moment as well.

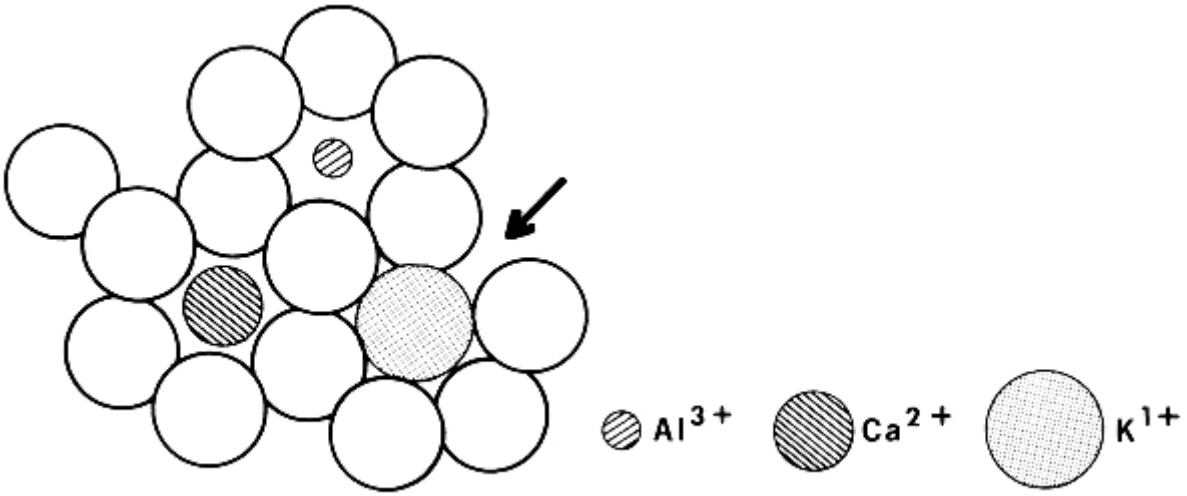

Figure 3.2 Accommodation of ions of different sizes in the hexagonal water structure; arrow indicates disruption of the water structure caused by the large K^{+} cation. After Lawrence and West 1982: fig. 3–6*b*.

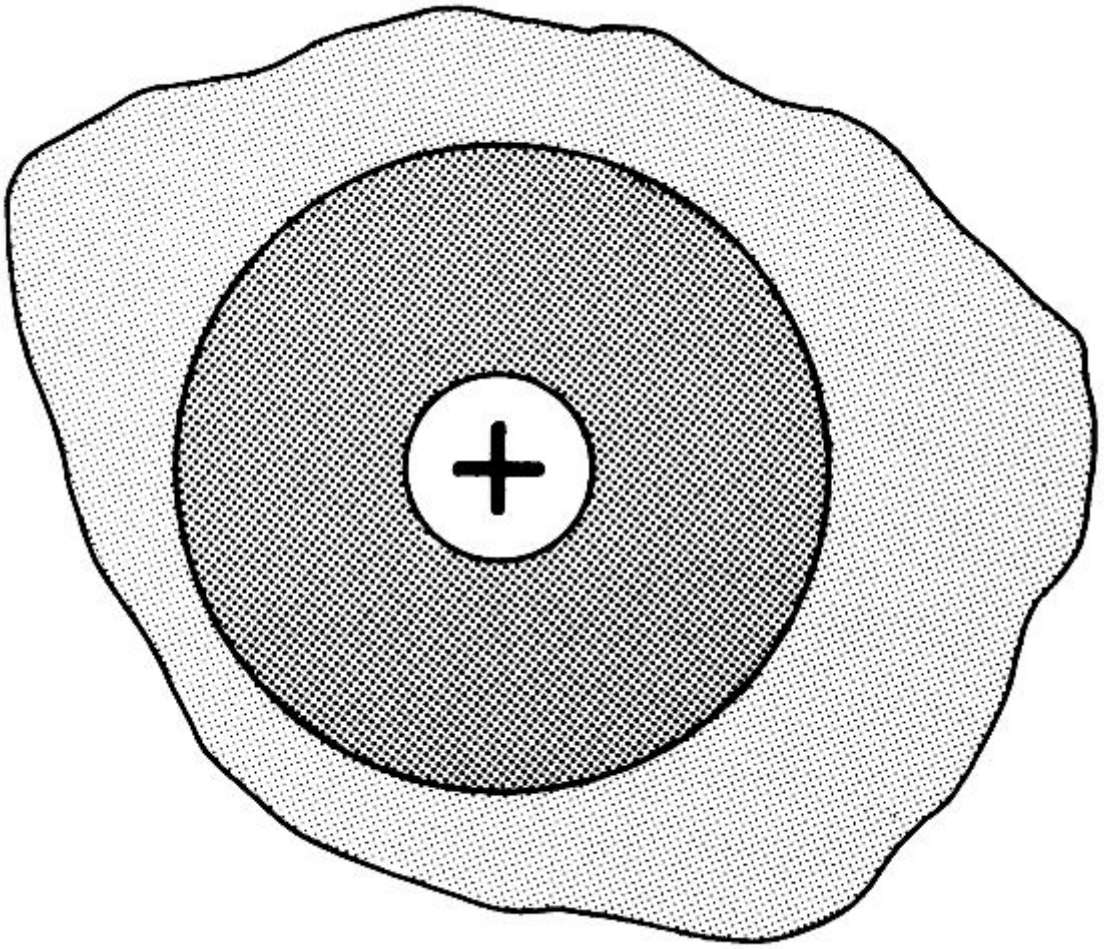

Figure 3.3 Model for the modification of the structure of water produced by the presence of a small cation (+). Heavy stipple indicates region of immobilization; light stipple indicates region of high disorder between immobilized water and normal water structure outside stippling. After Lawrence and West 1982: fig. 3–4.

To satisfy the charge deficiency of these ions, the surface sites of the clay platelets attract the dipole water molecule (and other ions), the OH^- and O^{2-} bonding with H^+ in water and the Al^{3+} and Si^{4+} bonding with the O^{2-} in water. This forms a layer or shell of adsorbed water a few molecules thick around the entire platelet, which then acts as a large ion or series of ions enveloped by a water layer. Although the interactions remain incompletely understood (Moore and Reynolds 1997: 120–24), this water can be held with varying degrees of tightness and it may be "nonliquid" (or rigid, immobilized, semicrystalline) (fig. 3.3), analogous in some ways to ice.

The thickness of this area of immobile water is a function of several factors. One is the attracted ions' size and charge: size is enlarged by small, highly charged ions, which fit into the water structure without disrupting it, whereas large, monovalent ions decrease immobilization and stability. Both monovalent sodium (Na^+) and divalent calcium (Ca^{2+}) cations have the same ionic radius, 0.98 Å, but in clays with adsorbed

sodium cations, the nonliquid water zone is smaller than in clays with calcium cations, and there is a considerably greater transition region to liquid water (Grim 1968: 251–52). Doubtless this is related to the fact that sodium-rich clays require less water to develop plasticity than do calcium-rich clays. The size of the immobilized water layer also varies among the clay minerals (Grim and Cuthbert 1945): kaolinite platelets, for example, have a pattern of charges on the edges that matches the hexagonal structure of water, making for an interlocking and stable structure.

3.2 Plasticity

Plasticity is the property that allows a clay, upon addition of a limited amount of water, to be shaped by pressure and to retain that form when the pressure is relaxed. Plasticity is lost when this adsorbed water is removed from the clay in air drying, but the form will be retained. Rewetting can restore plasticity, but the shaped form will disappear. Upon heating, clays become hardened in a permanent form, and above certain time-temperature conditions the capacity for regaining plasticity is permanently eliminated.

3.2.1 Factors Influencing Plasticity

Plasticity has its origins in the clay/water system and arises from a number of factors (Barna 1967; Bloor 1957; Grimshaw 1971: 496–504; Marshall 1955; Norton 1948). Key factors include clay particle size and shape, surface tension of the adsorbed water, adsorbed ions, clay and non-clay mineral components, clay deposit location, and organic content.

3.2.1.1 Particle Size and Shape

It has already been mentioned that clay particles are extremely small, generally less than 2 μm in diameter, and a considerable proportion of the smallest particles behave like colloids. In addition, they typically occur as flat lamellae or platelets, with an approximate 1:12 ratio of thickness to diameter. These shape and size considerations mean that the particles in a clay mass have a very large total surface area.

Some idea of the surface area of clay-sized particles, compared with sand or other particle-size grades, is revealed by calculating the surface area produced by successively subdividing a cube of some material (Lawrence and West 1982: 21). A cube of one cubic centimeter (1 cm^3) has a total surface area of 0.93 square inches. Dividing that cube into particles on the order of 0.1 mm in diameter would produce 93.0 square inches (600 sq cm) of surface area. If the original cube were divided into fine clay-sized and clay-shaped platelets 0.1 μm (or 0.0001 mm) in diameter, the total surface area would be just under 650 square feet (c. 60 sq m). Stated differently, 1 cm^3 of clay-sized particles has 1,000 times the surface area of an equal volume of coarse sand-sized particles.

Most of the properties of clay/water systems—and especially plasticity—result in large part from the interactions of clay and water at the surfaces of the clay particles. When water is mixed with a clay, the thin film of adsorbed water surrounding the platelets acts as a lubricant that allows them to slide over one another. Clay owes much of its plasticity to the characteristics of this adsorbed water, particularly its surface tension and adsorbed ions. The finer the particle size of a given volume of clay, the greater its plasticity, in part because a larger number of platelets, and hence a larger

surface area, is present. Plasticity is generally inversely proportional to particle size range.

3.2.1.2 Surface Tension

Surface tension refers to the intermolecular interactions of the thin films of water coating the clay particles, which act weakly to hold the clay particles together. Although in a plastic clay mass the water serves as a lubricant for the platelets to slide easily over each other, surface tension forces are simultaneously sufficiently strong to make it difficult to pull them apart, that is, to "shear" the entire mass.

Two points are important. First, the greater the total surface tension resulting from finer particles and thus more surrounding water, the greater the plasticity of the clay/water system . . . up to a certain limit. There seems to be an optimal—and rather small—amount of water necessary for any given clay to reach a plastic state. This amount must include enough water to satisfy the charge requirements on all available particle surfaces and to achieve lubrication, surface tension, and flow. Addition of water beyond this optimum results in reduced surface tension, reduced resistance to shear, and reduced plasticity, and the body moves beyond a plastic state to become soft and weak. If, on the other hand, insufficient water is added, the particles may not be close enough to each other to satisfy charge and surface tension requirements.

A second point concerns the channels or capillaries through which the water moves. Because surface tension increases with greater surface area and capillary volume per unit volume of clay, finer clays are more plastic than coarse ones, which have less surface area and a smaller total pore structure.

3.2.1.3 Adsorbed Ions and Rigid Water

The (relatively) enormous surface area afforded by clay platelets, and especially the colloid-sized particles in clay mixtures, presents a significant region for adsorption of ions from the surrounding water films, including the immobile water structure. Clay platelets typically have a net negative charge, which makes them act like ions and repel each other, remaining stable and separated or dispersed (deflocculated).

The ions in the adsorbed water film surrounding the clay platelets affect plasticity by influencing the platelets' dispersion and orientations. These effects depend primarily on the ions' size and valence, but also on their shape and tendency to hydrate. Other things being equal, plasticity increases as the charge of the ions increases and their size decreases. Large monovalent cations such as Na^+, K^+, or NH_4^+ tend to suppress plasticity by disrupting the nonliquid water structure and promoting disorder. Smaller, more highly charged divalent ions such as Mg^{2+} fit more securely into the holes in the lattice and have little disordering effect, thus increasing plasticity.

As noted, clays with Ca^{2+} cations have a larger zone of immobilized water around the particles than do sodium-rich clays and a more abrupt transition to liquid water. This is a factor not only in the variable amounts of water required to develop initial plasticity in these clays, but in the effects these ions have on plasticity when they are added in excess.

3.2.1.4 Clay Mineral Component

Individual clay minerals vary in plasticity. In general, and other things being equal, minerals with smaller particles, such as smectites, tend to be more plastic than those with larger particles, such as kaolinites. A further consideration is the clay minerals' varying propensities to adsorb and hold ions because of their different crystal structures and particle sizes. This property is known as their base, ion, or cation exchange capacity (CEC). Kaolins, for example, because of their two-layer structure and the arrangement of charges on the edges of the particles, have little tendency to adsorb ions (low CEC), whereas smectites, with their expanding three-layer lattices, have a high capacity.

3.2.1.5 Deposit Location and Organic Matter

The origins and locations of clay deposits affect their plasticity. Because of sorting and weathering during transport and redeposition, sedimentary clays such as ball clays are usually finer in particle size and more plastic than are primary clays such as china kaolins. Primary clays may include relatively large amounts of coarse and angular parent material, which means that particles in the clay size range make up only a small fraction of the total, and as a result they are very low in plasticity.

Sedimentary clays may be finer than primary clays also because they are often mixed with organic matter such as bacteria and acids in the process of deposition, increasing plasticity. Ball clays, for example, in addition to being fine in texture, are typically high in organic matter. The same is true of estuarine or lacustrine clays, which are often gray to black from organic matter; if not too sandy, these may be plastic to the point of stickiness.

3.2.2 Measuring Plasticity

The definition of plasticity highlights deformation of the clay by pressure, and three major forces or stresses are involved: (1) compressive force—pressing on a wet clay; (2) tensile force—stretching or pulling the clay mass (extension); and (3) shear—simultaneous application of opposing forces on the clay. All these forces create stresses that can eventually bring about cracking and rupture. They, and hence plasticity, can be measured by several methods in commercial ceramic applications, many of which are concerned with the pressures involved in extruding clays, and also in soils sciences and

engineering (Andrade et al. 2010; Carty and Lee 1996; Oliveira Modesto and Bernardin 2008; Reeves et al. 2006: 228–29).

The property of plasticity is described in ceramic industries by several terms that refer to the deforming forces applied to a clay, to the amount of water at which deformation occurs, or to both. These terms include:

- Yield point: the point at which compressive stresses start changing the shape of the plastic mass as the clay begins to become soft and malleable rather than remaining stiff and unyielding. It may be measured by the force per unit area applied to the test material in pounds per square inch (psi) or kilograms per square meter.
- Extensibility: the amount of deformation a clay can withstand (in inches or meters) beyond the yield point before cracks appear.
- Working range: the interval between yield point and the upper boundary of extensibility.
- Workability (also working range): the variable amount of water that must be added to—that is, mechanically combined with—a dry clay to make a mass that can be satisfactorily formed.
- Plastic limit: the water that allows a clay to be repeatedly rolled into a thin needle or thread. The plastic limit is the amount of moisture retained when the needle breaks at a diameter of about 3 mm.
- Liquid limit: the water that softens the clay to the point that it becomes semi-liquid and flows.
- Water of plasticity (%WP): the amount (by weight) of water required to develop optimum plasticity in a dry clay.

Various industrial tests measure the plasticity of clays based on these properties, largely on the principle that moisture content is directly related to strength and to resistance to some aspect of applied forces that cause deformation or rupture. The Pfefferkorn method, for example, measures plasticity in terms of the moisture content of test samples under strain of a weight dropped on them. Atterberg's plasticity index (or Atterberg limits) measures plasticity as the difference between plastic and liquid limits as described in ASTM Standard D4318 (ASTM 10). This test is commonly used to test the structural properties of soils.

Box 3.1 Assessing Plasticity: %WP

A clay's plasticity can be determined adequately, though nonquantitatively, by a skilled potter through "feel" and experience. Potters will squeeze a lump of clay, bite it, rub a small pinch between thumb and forefinger, or make a loop of it to judge its plastic characteristics. A plastic clay feels smooth or slimy and is usually a fine clay, whereas one that is stiff usually feels coarse and gritty. Even someone inexperienced can make some determination of a clay's working properties based on intuitive concepts of plasticity.

Commercial tests and testing devices are not always appropriate for natural clays used by village potters or sampled near archaeological sites, and other assessment procedures, some of them less precise, may be used (see Bronitsky 1982; Gosselain 1994; Greger and Berg 1956; Norton 1938). Optimum plasticity is a subjective judgment, dependent upon intended use and the individual potter's sense of what feels right.

Water of plasticity is an easy assessment, calculated by slowly adding water from a graduated cylinder to a standard weight of dry clay (for example, 100 g). First, the amount of water required to develop initial plasticity (a rough estimate of the yield point) is recorded, and then the additional amount giving full plasticity after continued mixing. Because 1 cc (or 1 ml) of water equals 1 g of weight, the volume is equivalent to the weight of water; thus the amount added to 100 g of clay is equal to the clay's %WP. Adding additional water, to the point that the clay becomes sticky and loose, gives the upper limit of the working range. The upper and lower amounts are a measure of the range of workability. For any given clay, %WP calculations may be given as a range rather than a single number, often around 20% by weight.

Another way to measure water of plasticity is by comparing the weight of a wet clay object with its dry weight. This figure is multiplied by 100 to express it as a percentage:

$$\%WP = \frac{\text{weight}_{wet} - \text{weight}_{dry}}{\text{weight}_{dry}} \times 100$$

In effect, this calculation bases the measure of plasticity on the amount of water lost from the clay in drying, the weight loss corresponding to the water added to the dry clay to achieve plasticity.

A similar concept of plasticity is expressed by the coefficient of plasticity, which is the ratio of the shrinkage water to the total water content required for forming and provides a relative degree of plasticity (Barna 1967: 1092).

Yield point and extensibility are inversely proportional: a clay with a high yield point will have low extensibility, tending to crack when force is applied. These relations play a significant role in workability. Some clays have a wide working range and can be worked into the desired forms without cracking when both relatively wet and relatively dry. Other clays have a narrow range: they are stiff until a certain amount of water has been added, but with just a little more they slump and lose their firmness. A good potter's clay balances the two opposed characteristics, so that it has both a moderate yield point and a moderate extensibility. In general, the coarser the texture, the

narrower the working range. Finer clays typically require more water to develop plasticity, because they have more particles per unit volume and also a more extensive pore or capillary system for carrying water. Coarser clays, in contrast, have larger capillaries but comparatively fewer of them (i.e., a smaller total pore structure), and usually need less water to make them plastic.

Table 3.1 Water of Plasticity Ranges of Several Clays

Clay Type	%WP
Washed kaolin	44.48–47.50
White sedimentary kaolin	28.60–56.25
Ball clays	25.00–53.50
Plastic fireclays	12.90–37.40
Flint fireclays	8.89–19.04
Saggar clays	18.40–28.56
Stoneware clays	19.16–34.80
Brick clays	13.20–40.70

Source: After Nelson 1984: 322.

Plastic limits vary in practice with the kind of clay mineral, the intended use, and the pressure individual potters exert with their hands as they form their pots. Clays with a relatively broad working range and varying useful consistencies (wetter versus drier) for hand building or throwing are sometimes described as fat or rich. They are typically sticky, fine, and very plastic. Smectite clays, for example, are often fat clays, as are ball clays. A good clay for throwing on a wheel should have a relatively wide plastic region, because it must flow easily with the centrifugal forces of the wheel, but it should not dry out excessively or lose plasticity from the evaporation caused by rapid spinning. In contrast, stiff, lean, or short clays are usually coarse, with a relatively narrow working range. For hand building, particularly of large objects, a stiffer clay (with a higher yield point and lower extensibility) might be serviceable. Table 3.1 gives ranges of %WP for some common clays.

Plasticity is a desirable characteristic of clays up to the point of excessive stickiness. Because plastic clays are preferred by studio or art potters, traditional potters, ceramic engineers, and in industry, various practices may be followed to increase plasticity in a comparatively stiff clay. For example, adding organic material, particularly acids, will increase the plasticity of alkaline clays by lowering the pH (hydrogen ion concentration, or acidity versus alkalinity) to a neutral or slightly acid level of 6–7 (Grimshaw 1971: 505). Some art potters add yogurt, vinegar, beer, or starch to alkaline commercial clays, increasing acidity as well as contributing bacteria, which also enhance plasticity. Aging a clay—over weeks or even generations—increases plasticity; the process apparently works by allowing the water to reach all clay particles and promoting the action of bacteria and acids, altering the pH, and perhaps increasing the fineness of the clay (see

Glick 1936). The growth of molds during aging, particularly if organics were added to the clay, can cause other problems in forming and firing, however (Fina 1985).

Plasticity can also be increased by mixing a stiff clay with another clay that is finer and more plastic, for example adding a ball clay to kaolin for porcelain. A fresh clay can be combined with part of an older batch that has been mixed and aged, even for a short while. In industry, cations of a high charge may be added or the amount of monovalent ions decreased in the system, both of which will disrupt the rigidity of the adsorbed water and increase plasticity.

3.3 Ions and Organics

Naturally occurring clays rarely exist as pure, monomineralic deposits. Instead, they usually incorporate a variety of inclusions and impurities in all size ranges, or potters may add such materials to modify their properties. Here, discussion focuses on extremely fine colloid-sized material (excluding the clay mineral fraction itself).

Colloidal-sized particles and ions can have big impacts on the behavior of clays in terms of plasticity, drying, shrinkage, and green strength. The colloidal fraction of a clay comprises particles 0.001 mm (or 1 μm) or less in diameter. Particles in colloidal suspensions repel each other, being kept apart by their like charges as well as by Brownian movement, the continuous agitation of colloidal particles caused by collisions with molecules in the surrounding solution. Two kinds of colloidal matter are important in understanding clay sediments: organic and inorganic (represented almost entirely by very fine clay mineral particles).

Colloid-sized particles in a ceramic system affect plasticity and shrinkage through their enormous surface area. The large surface area increases the volume of water in a clay mass and expands the opportunities for adsorption and exchange of ions, which can change the dispersion of the clay platelets (Grimshaw 1971: 465–73).

3.3.1 Ions

Clay minerals differ in their capacity to adsorb ions, as measured by CEC. Cation exchange capacity refers to the ability of fine clay platelets to loosely adsorb ions dissolved in the water films surrounding them. Some surfaces can preferentially adsorb certain ions from solution, and one ion may be exchanged for another because the bonding is loose, but not all ions are replaceable or exchangeable. CEC is traditionally expressed in milliequivalents (meq, or equivalent atomic weight) per 100 g of dry clay at a neutral pH of 7 (Carroll 1959).

Table 3.2 Range of Cation Exchange Capacity of Some Clay Minerals (meq./100 g at pH of 7)

Clay	Norton	Grim	Carroll
Kaolinite	2–5	3–15	3–15
Halloysite	3–15	5–10	5–10
Hydrated halloysite	20–35	40–50	40–50
Vermiculites	100–150	100–150	100–150
Illites	10–40	10–40	10–40
Palygorskite group	20–30	3–15	20–30
Montmorillonite	75–150	70–100	70–100
Ball clays	7–30		
Smectite		80–150	80–150
Chlorite		10–40	10–40
Allophane		25–50	~70
Glauconite			11–20+

Source: Carroll 1959; Grim 1968: table 7-1; Norton 1970: table 9.1.

Several related explanations of ion adsorption and exchange in clays appear to operate. One is that ions satisfy broken bonds on the edges of clay particles, which themselves act as anions (negatively charged ions): particles adsorb positive ions onto their surfaces and negative ions onto their edges. A second type of ion exchange is lattice substitution—that is, the substitution of certain ions for others within the lattice structure, rather than on particle edges and surfaces. This appears to be particularly common in smectites and vermiculites and largely accounts for their high CEC. Most of these substitutions occur in the octahedral layer, with magnesium and iron particularly substituting for aluminum. A third mechanism involves satisfying the charge of the hydrogen of exposed hydroxyls. In addition, small quantities of three-layer minerals may adhere to the surfaces of other clay platelets (e.g., kaolins), thus increasing the CEC (Ma and Eggleton 1999). In general, the finer the clay (and hence the greater the surface area), the greater the exchange capacity (see, e.g., Johnson 1949; Johnson and Lawrence 1942).

Table 3.2 gives the CEC values of some common clays: clays with extremely fine particle size and expanding lattices (smectites), as well as vermiculite, have high exchange capacities, and substitutions within the lattice account for about 80% of their total exchange capacity (Grim 1968: 194). Kaolins, on the other hand, because of their

two-layer structure and the arrangement of charges on the ends of particles (an arrangement very close to the hexagonal structure of the water film), have low exchange capacity, and exchange takes place primarily on the edges and on the basal hydroxyl surface (Ma and Eggleton 1999).

Clays are selective in the kinds of ions they adsorb. In general, trivalent ions are adsorbed more strongly than bivalent ions, and bivalent more strongly than univalent. The most common exchangeable cations in clays are Ca^{2+}, Mg^{2+}, H^{+}, K^{+}, NH_4^{+}, and Na^{+}; common anions are SO_4^{-}, Cl^{-}, PO_4^{3-}, and NO_3^{-}. The order of their replacement power is highly variable, depending on concentration, size, temperature, and the presence of other ions. Monovalent ions, in addition to being less adsorbed, are usually larger; they have lower bonding energy, are more mobile, and diminish plasticity by disrupting the nonliquid structure of the water films surrounding the clay particles. The trivalent and divalent ions, more highly charged and smaller, increase plasticity because they fit more securely into the holes in the nonliquid water lattice.

3.3.2 Flocculation

Ions are important in a clay/water system because, by filling the electrically unsatisfied sites on the clay particle surfaces, they affect the arrangement of the particles and can contribute to—or alter—a deflocculated or flocculated state (Johnson and Norton 1941; Scripture and Schramm 1926). These states are also related to the pH of the clay.

An example of a deflocculated system is a colloidal suspension: colloid-sized particles permanently suspended in solution because the particles repel each other owing to their electrostatic charges (van Olphen 1977). In the case of the clay/water system, the tiny negatively charged clay platelets are, in effect, suspended in surrounding water films. Because the particles repel each other, these clays exist as stable dispersed suspensions that resist settling. Deflocculation usually occurs under neutral to alkaline conditions. Drying of a deflocculated system takes place with relatively lower shrinkage than in flocculated clays, at least along one dimension; dried products exhibit high green strength. Deflocculated clays are the usual basis for slips, which may be used as surface coatings of a clay body or for casting in molds (slip casting). Such slips have minimum viscosity or resistance to flow as well as a high solids content—many clay particles per unit volume.

In a flocculated system, by contrast, the suspension is destabilized and colloidal particles come into contact with each other in an edge-to-face structure. This occurs because negatively charged surfaces are attracted to positively charged edges. The particles form aggregations or “flocs” which may or may not settle or return to a deflocculated state. Flocculated clays may be described as highly viscous, with large amounts of water trapped between the particles; drying shrinkage is usually high.

Lowering the pH of the clay-water system will bring about flocculation, and thus flocculants are usually acids, or salts acting as acids. For example, adding organic

material will lower the pH to a neutral or slightly acid level of 6–7 and increase the plasticity of alkaline clays. Small (2 μm) cations such as calcium or magnesium (in the form of $CaSO_4$ and $MgSO_4$), for example, will flocculate a system, increasing its stiffness. Sodium and potassium (both monovalent cations) are poor flocculators. Some cations such as sodium in basic salts such as Na_2CO_3 or Na_2SiO_3, or alkalis such as ammonia or Calgon™, will deflocculate a flocculated clay system, making a stiff clay softer and more plastic, and also reduce shrinkage. Too much of these additives can reflocculate the system, however (Brody 1979: 28–29).

3.3.3 Organics

Flocculation/deflocculation and plasticity can be affected by organic colloids, collectively referred to as "humus" in soils studies. These comprise three classes of materials: fulvic acid, humic acid, and humin. Organics contribute to the acidity of soils or clays, particularly in moist, humid areas. Colloidal humus particles are very small (at least as small as the smectite clays), are thought to be noncrystalline, and have an extremely high CEC. Although the charge of the particles is pH dependent, it is generally negative so that, like clay particles, humus may be thought to consist of negatively charged particles surrounded by positively charged cations. Organic material in a clay (see, e.g., Worrall 1956) generally increases plasticity and may be suspected when a dark-colored unfired clay is sticky. Organic matter may also add to the dry strength of extremely sandy clays by increasing the total amount of finely particulate binding matrix in the mix.

Virtually all clays contain some organic material, if only a very small percentage. Primary or residual clays typically contain less organic matter than secondary or sedimentary clays, and surface clay soils may have 5% to 10% or more. Ball clays are commonly high in organics (as well as salts). Besides affecting plasticity, organic matter also influences the color of a fired clay piece.

4 Non-clay Constituents

> Western potters from the early days of industry and especially in making porcelain, have travelled further and further away from a natural conception of clay towards an ideal of over-refined mixtures which are aptly called pastes. Up to a point this has been a necessary tendency in the stages of standardization, but . . . the sooner we return to a healthier understanding of clay and melted stone the better.
>
> Leach 1976: 43

Most pottery is a mixture of clay, as defined mineralogically and granulometrically, and non-clay constituents. These latter may be naturally present in a clay deposit or purposefully added by the potter to modify the clay's properties. Inclusions in any clay body play significant roles during all steps of pottery manufacture—in the forming, drying, and firing phases—as well as in the use-related properties of a finished vessel. This chapter reviews various kinds of non-clay constituents, their roles, and their identification.

4.1 Coarse Inclusions

Natural clays are usually mixtures of clay minerals and non-clay mineral components occurring in a range of grain sizes, largely reflecting the circumstances of weathering and deposition. Coarser particles or clasts, typically angular to subangular in shape, are common in primary clay deposits located relatively near their parent rock. Clasts may vary from pebble-sized (very coarse, greater than 4 mm in maximum dimension), through gravel (between 2 and 4 mm), down to the sand, silt, and clay-sized ranges (fig. 2.2). Recall that sand refers to a particle-size category, not to a specific mineral, although the predominant sand- and silt-sized mineral in clays is usually quartz. However, sands also may be calcium carbonates, volcanics, or a mixture of many materials including accessory minerals such as micas, feldspars, hornblende, and ferric material (the last often occurring as finely particulate coatings on the larger grains).

The coarse material in a natural clay is largely responsible for the property known as texture: the proportion, size, and shape characteristics of the grains in a clay material, whatever their origin or their mineral identity. Texture is typically assessed by comparing particle-size fractions against some standard scale established by geologists or pedologists (e.g., fig. 2.3).

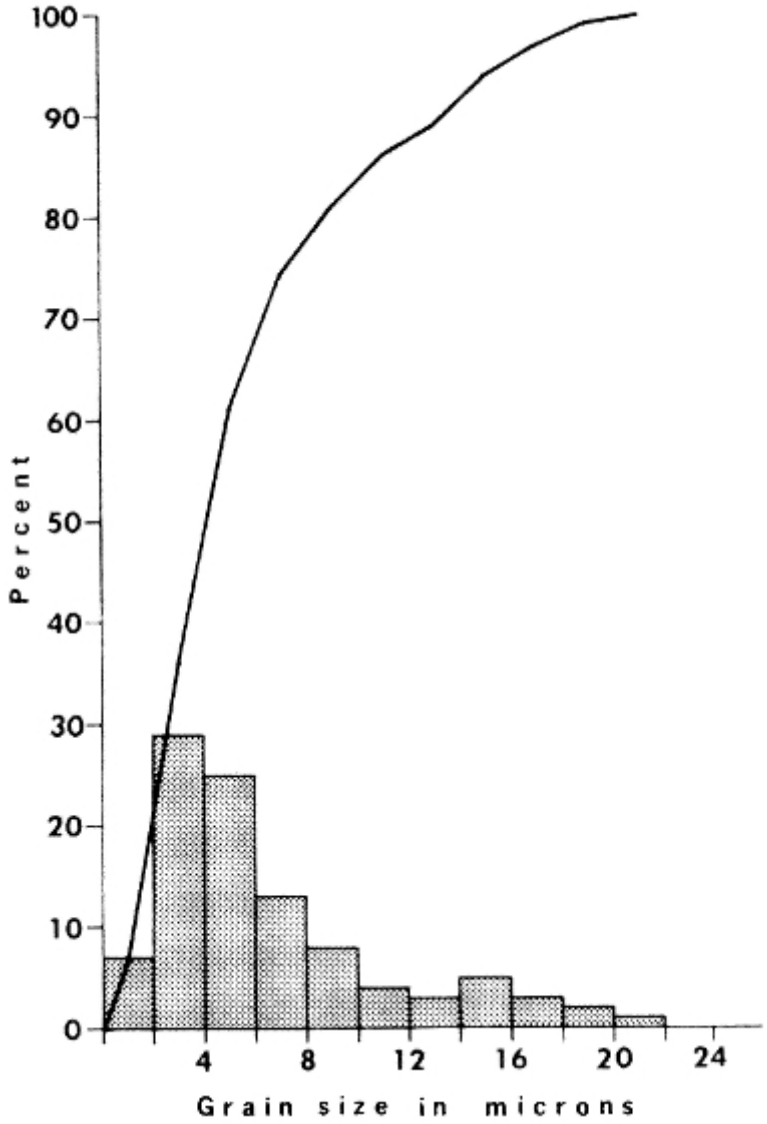

Figure 4.1 Particle-size distribution of a hypothetical clay determined by the suspension method, showing by histogram and cumulative percentage graph the percentage weight of the sample finer than a particular size (in micrometers). After Grimshaw 1971: fig. VII.7.

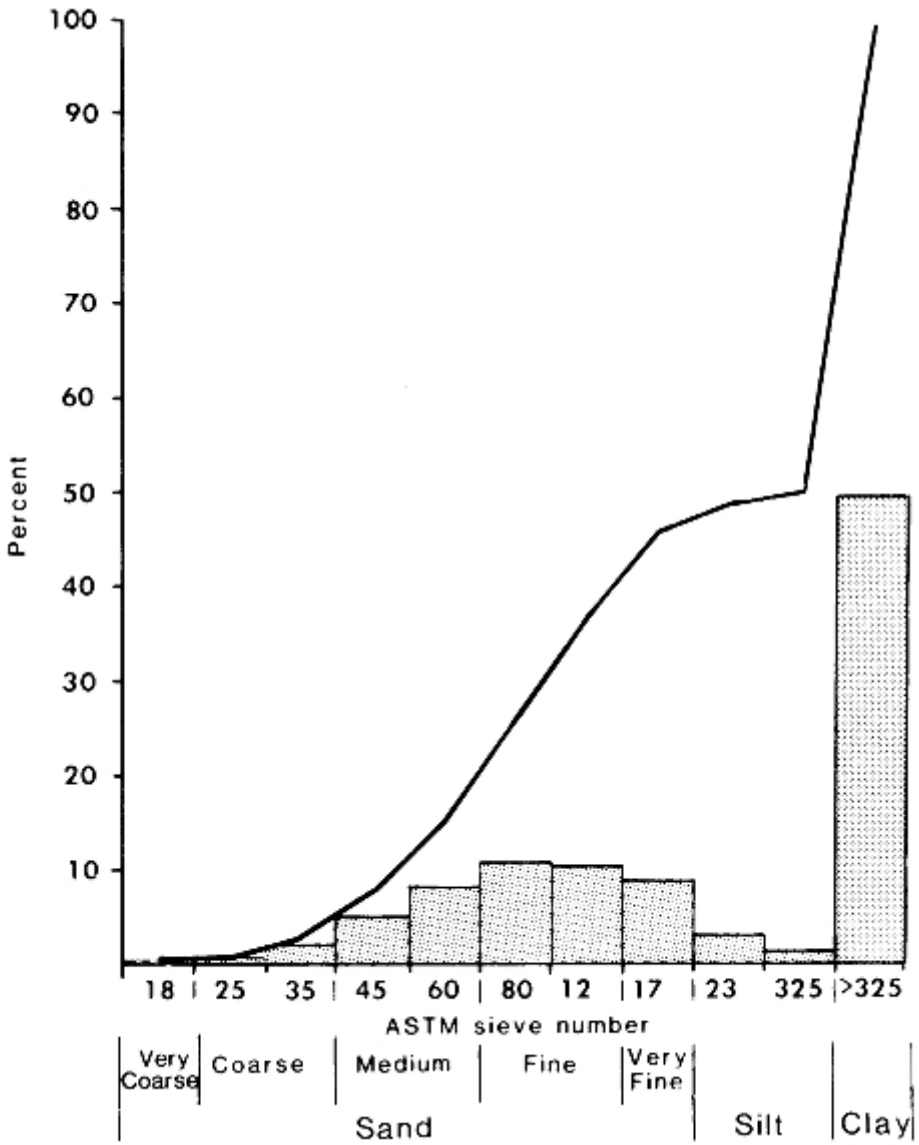

Figure 4.2 Particle-size distribution of clay C-16 from Suwanee County, Florida, determined by sieving, showing the percentage weight of particle-size fractions left on ASTM sieves of different sizes (see fig. 2.2 for mm equivalents). Data from Cordell 1984: appendix L

Two methods are commonly used to separate particle-size fractions of sediments: the suspension (or sedimentation) method (fig. 4.1) and the sieving method (fig. 4.2). The suspension method is based on Stokes' law, which permits calculation of the settling time of particles of different size (diameter) and density in a given fluid of known density and viscosity. Various techniques employ pipettes, hydrometers, and settling tubes, and they are usually applied to fine, subsieve-sized sediments (Shackley 1975: 116–33). Sieving provides a relatively easy method for studying the particle-size distributions of sandy or silty natural clays, and the extracted fractions can be used for additional mineral analyses.

Box 4.1 Particle Size Fractions

Sieving may be done either dry or wet (Shackley 1975: 109–15), but because clay usually consists of aggregated particles it is usually necessary to use wet sieving. A weighed amount of clay, dried at 110°C, is soaked in water, then washed through a series of graded sieves, such as the American Society for Testing and Materials (ASTM) series. The sieves should represent the approximate size divisions of sand (coarse, medium, fine), silt (coarse, medium, fine), and so forth. By comparing the relative percentages left on the sieves with a scale such as the Wentworth scale (fig. 2.2) or with a ternary diagram (fig. 2.3), the clay may be described as sandy or silty.

Wet sieving is not very accurate, especially for the finest particle sizes, which are usually lost; for this fine fraction, sedimentation methods should be used. Furthermore, it is necessary to dry the sieved fractions before reweighing.

Like plasticity, texture can be judged imprecisely—though often very effectively—by "feel" when a small amount of a wetted clay is rolled between the fingers. Indeed, the texture and particle size range of nonplastic inclusions in a natural clay strongly affect its plasticity: the greater the quantities and sizes, the lower its plasticity. A coarse-textured clay is more stiff or lean, tends to crack during forming, and has a narrow working range.

Besides texture, a second property affected by particle size is drying behavior: coarser clays tend to dry faster than finer clays, with less shrinkage. Sandy or coarse clays have a more open structure, with fewer but larger pores per unit volume, and the non-clay particles have no water films, meaning less water in the system to begin with. Thus the movement of water from the interior to the surface, where it evaporates, is enhanced and the danger of warping is reduced.

Green strength, the ability of a formed and dried but unfired piece to withstand mechanical stress, is generally higher with very fine particle sizes. Greater amounts of large-sized inclusions or inclusions in only a narrow size range—for example, silty clays lacking both a considerable clay-sized fraction as well as coarser material—tend to lower green strength.

4.1.1 Three Common Minerals

Three kinds of mineral grains, quartz, feldspar, and calcium-based minerals, are particularly common in ceramics, whether naturally present in clay or added by potters. Of these, the most common is free crystalline silica, SiO_2, formed of the two most abundant elements in Earth's crust. Silica is important in determining the physical and mechanical properties (shrinkage, porosity, strength) of clay bodies. This function is influenced by its particle size and crystalline form:

- Macrocrystalline silica, such as quartz or quartz sand, is composed of the same tetrahedral structural units that compose the silica layers of clays, with few or no significant atomic substitutions. In quartz, however,

the tetrahedra are arranged not in a sheet-like structure, but in spiral chains.
- Polycrystalline quartz is exemplified by quartzite, a metamorphosed sandstone.
- Cryptocrystalline quartz comprises flint, chert, chalcedony, agate, and jasper. Flint is finely crystalline (micro- or cryptocrystalline) hydrated silica, containing 1% water in molecular form; it is less dense than sand, having fine pores as a consequence of this structure. In the modern commercial or studio pottery business, silica may be referred to as potter's flint or sand and is often found as ground glass.
- A fourth class of silica—an amorphous form including organic, opaline, and biosilica—is occasionally found in pottery.

A second important category of inclusions in ceramic bodies, particularly those to be fired at high temperatures, is feldspar. A large and abundant family of aluminosilicate minerals consisting primarily of SiO_2 tetrahedra, feldspars have significant substitutions of aluminum for the central silicon atoms, plus additional cations—K^+, Na^+, or Ca^{2+}—that maintain electrical neutrality. The feldspar family thus consists of a continuum of minerals, with graded compositions based on the proportions of these three key elements: K-rich or potash feldspars include orthoclase and microcline; Na-rich soda feldspars (albite) and Ca- or lime-rich feldspars (anorthite) together constitute the plagioclases. Because the number of replaced silicon ions may vary to maintain balanced electrical charges, the proportion of silica varies in the several kinds of feldspars. Rarely do other ions substitute for these in the feldspars; iron, for example, is never part of the feldspar composition. Because feldspars are also the primary parent materials of clay minerals, they are often present in small amounts in natural clays, especially primary clays, as a result of incomplete weathering of rocks such as granites and basalts, and often with associations of mica.

A third important group of non-clay minerals in pottery is the calcium family (see Grimshaw 1971: 279–80). Calcium most commonly occurs in various forms of calcium carbonate ($CaCO_3$), including calcite, limestone, and aragonite, or as calcium sulfate or gypsum ($CaSO_4$). Clays in which these forms occur naturally are described as calcareous or marly sediments, commonly deposited in lacustrine or riverine environments in a limestone (or other carbonate) geological region. Otherwise calcium may be added to clay in various forms, including calcite, limestone, shell (aragonite), and bone (calcium triphosphate, $Ca_3[PO_4]_2$, or calcium hydroxylapatite). Calcined animal bone ash is an ingredient in English bone china. Large particles of calcium carbonate may decompose on heating, leading to the spalling damage known as lime popping in the fired piece.

4.1.2 Triaxial Bodies

Today's studio potters and ceramic industries use triaxial bodies, which are standard mixtures of three basic components, the proportions varying with the product desired (see fig. 4.3). One component is a clay (or more than one clay), which provides plasticity and dry strength. To this is added a filler or aggregate, typically flint, quartz sand, or a chemically inert material (grog), which limits shrinkage, reduces drying time,

and eliminates cracking. As noted, much of the influence of quartz in a clay body relates to particle size; for example, approximately 50% of potters' flint is below 30 μm. The third constituent is a cementing component or flux—typically a K- or Na-feldspar or other alkali mineral, such as nepheline syenite (having both K and Na in its composition)—which promotes melting, helps develop fired strength, and reduces porosity.

Triaxial bodies are attempts to create, though with much finer mean particle size and far less range of variation, the mix in an ideal natural clay deposit: a range of interlocking particle sizes for strength and porosity, and the desired strength or purity to withstand high temperatures (as in cooking). A typical triaxial body might have 50% clay, 25% quartz, and 25% feldspar; the clay might be a mix of kaolin with particle sizes of 2 μm and ball clay at 0.5 μm, and the quartz and feldspar particles might average 40 μm in diameter (Norton 1970: 259).

Having to add these materials to commercially available, over-refined clays that once contained them naturally is analogous to adding vitamins and fiber back to over-refined flours in commercial white bread. The irony has not gone unnoticed. As in the epigram, Bernard Leach, a famous potter and philosopher of art pottery, has commented on the paradox:

> To dig a single clean clay in the vicinity of the kilns was the habit of the old country potters and it is one which can be recommended to the studio potter of today. . . . He should not want to standardize, or to depend entirely on those reliable but uninteresting substances which the potter's merchant offers to the trade. What usually happens is that the studio potter in search of quality is forced by ignorance or convenience to buy standardized raw materials and then to introduce impurities artificially in order to obtain, not nearly so successfully, what he might have had direct from nature.
>
> *(Leach 1976: 43–44)*

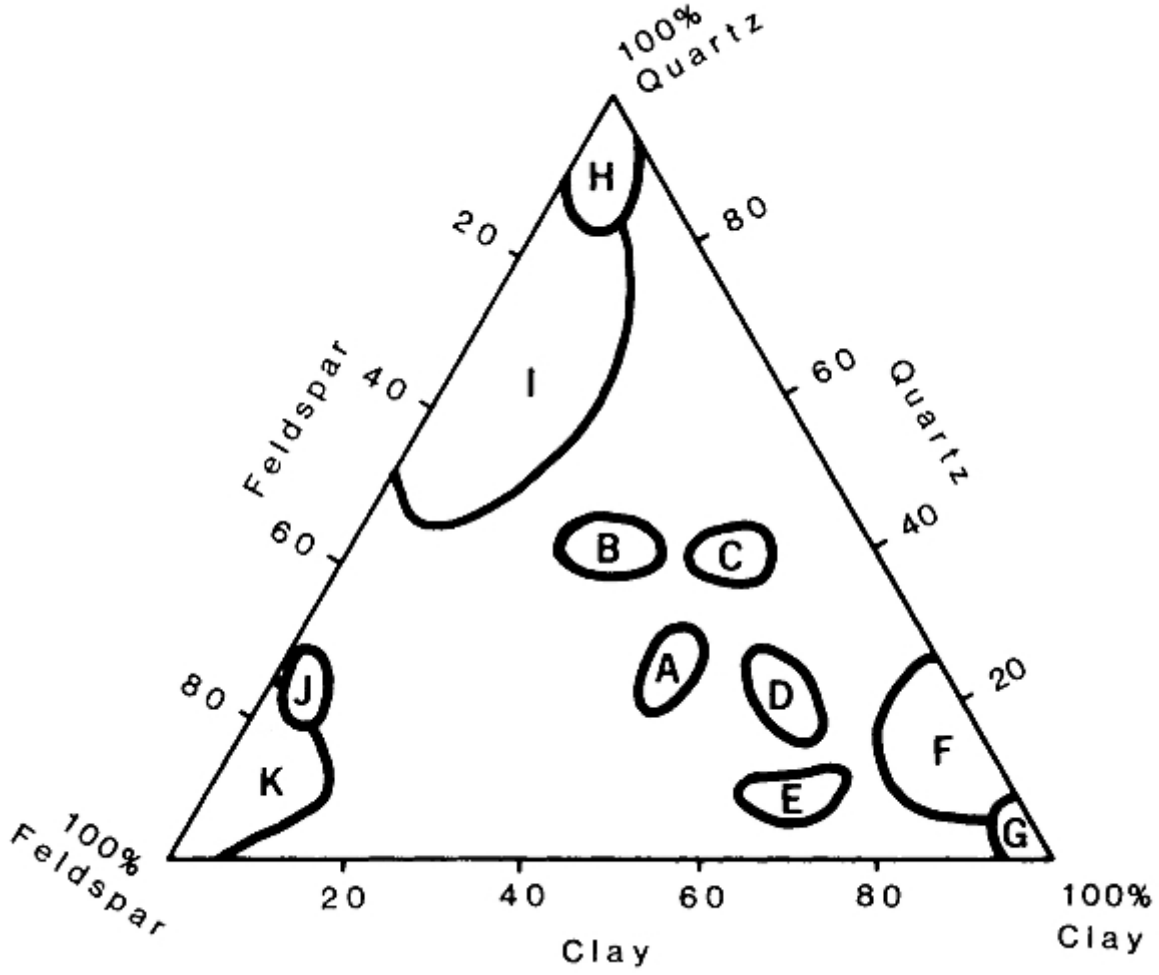

Figure 4.3 Raw ceramic materials and triaxial bodies: *a*, American electrical porcelain; *b*, Chinese and Japanese porcelain; *c*, stoneware; *d*, European cookware; *e*, European electrical bodies; *f*, raw kaolin; *g*, washed kaolin; *h*, quartz sands; *i*, feldspar sand; *j*, American dental porcelain; *k*, feldspars. After Norton 1970: figs. 12.2, 12.3, 12.4.

4.2 What Is Temper?

Ancient and traditional potters today add varied materials to their clay mixtures to modify the plastic and performance characteristics. These additions, commonly called temper by archaeologists, are intended to modify workability and porosity; reduce time, shrinkage, and deformation during drying; and improve firing behavior. For example, tempering materials may increase plasticity, decrease stickiness, reduce drying shrinkage, lower the vitrification point in firing, or increase the strength of the fired piece. The term temper may be used rather casually in archaeological pottery studies: everyone seems to know generally what it is but there is little agreement on a precise definition, a problem noted as early as the 1930s (March 1934; see also Arnold 1974; Shepard 1964).

4.2.1 Kinds of Temper

A survey of the archaeological and ethnographic literature reveals that virtually any substance can be added to a clay to modify its properties at any stage before drying a formed object. A great variety of materials, including minerals and organics (plant and animal remains) may serve these purposes (see Table 4.1; Rye 1981: 31–36; Shepard 1976: 26–27).

Mineral tempers are most common, including various types of crushed rock (limestone, sandstone, andesite, trachyte, basalt, schist, etc.), sand (usually quartz), and volcanics such as ash or sand and pumice (even obsidian; Palumbi et al. 2014). Volcanics are a particularly useful temper, contributing little weight to the fired piece but adding considerable strength. Asbestos, a family of fibrous silicate minerals, was added to early pottery in Finland (Personen and Leskinen 2010: 311) and among traditional potters in Uganda (Wilson 1973: 301). Considered a carcinogen today, this mineral has a strength and thermal stress resistance that would have made it a useful addition to cooking vessels.

Table 4.1 Characteristics of Some Common Kinds of Temper

Characteristics	Shell		Carbonate	Sherd	Mica	Organic	Crushed Rock	Volcanic Ash	Quartz Sand	Biosilica
	Calcined	Uncalcined								
Advantages										
Platy—blocks crack propagation	x	X			x					
Angular—adds strength				x			x	x		x
Crushes easily	x									x
Has low or comparable thermal expansion	x			x						
Increases porosity						x				
Disadvantages										
Platy—prone to laminar fractures	x	X			x					
Hard to crush or process		X	x	x			x			
Rehydrates after firing	x	X	x							
May weaken body by shape or porosity						x			x	
Shape[a]	P	P	I, S, R	I, A	P	I, P	A	A	R, S, I	A
Natural abundance in clays[b]	N	M	Y	N	M	N	M	N	Y	M

[a] P, platy; S, smooth; I, irregular; A, angular; R, rounded.

[b] Y, commonly found in quantities sufficient to act as temper; M, may occur in variable to moderate quantities in clays, may or may not be sufficient for tempering; N, does not commonly occur in clays.

Another substance used to modify clays' properties is salt (NaCl). Often added to calcareous clays or clays tempered with calcareous materials such as calcite or shell (Klemptner and Johnson 1986; Matson 1971: 66–67; Rye 1976; Rye and Evans 1976: 39, 91), salt appears to counteract the tendency of calcite to spall the surfaces of low-fired pottery and may also lighten the surface color (Brooks et al. 1974: 52). Potters among the

Seri, non-agriculturalists in coastal northwestern Mexico, however, claimed that the salt in sea water caused their pots to crumble (Bowen and Moser 1968: 94).

Clay itself may be a temper, and it is not uncommon for potters to mix clays of different properties, although once in the paste added clays might not necessarily function as plasticizers (compare Arnold 1971: 35–36, with Rye and Evans 1976: 20). Such mixing is particularly likely in areas where large deposits of relatively coarse residual clays are common (Bishop et al. 1982: 317; Buko 1984: 360–61). Some Pakistani potters, for example, use two parts of a relatively coarse clay modified with one part of a finer plastic clay (Rye and Evans 1976: 20). Gamo potters in southwestern Ethiopia mix three to four kinds of clay to make their pots, claiming that they contribute varying degrees of plasticity and strength (Arthur 2006: 34–35). The earthenware bodies of Spanish majolicas were mixtures of two clays, one red-firing and the other white-firing and calcareous, which lightened the fired color and assisted in the "fit" of the tin enamel coating (Lister and Lister 1987: 256–57; Magetti et al. 1984; Molera et al. 2001: 339). The calcareous clay was carefully pre-processed to avoid the dangers of lime popping.

Shell tempering is fairly common but benefits from some preparation. Mollusk shells are primarily aragonite, a biomineral form of calcium carbonate with a different lattice structure. They are typically difficult to crush, so they may be calcined or heated to facilitate the process. Aragonite changes to calcite when it is heated to about 500°C, with a concomitant expansion, and the structural changes make crushing easier. In addition, calcite has a lower coefficient of thermal expansion than aragonite, making it more suitable as a temper for cooking vessels. If shell is calcined at higher temperatures (at or above 750°C), however, and then added to clay and fired, the subsequent rehydration of the decomposition product (CaO) with atmospheric water and then CO_2 after cooling will lead to lime popping. On the other hand, prefiring to 750°C will prevent evolution of CO_2 on firing, with its effects of increasing porosity and bloating. Calcite decomposition can be retarded by firing in a reducing atmosphere.

Many different kinds of organic materials of either plant or animal origin or composition may be added to clays. Plant materials include grass or plant fibers, chaff or straw from cultivated grains such as rice or wheat, cattail fuzz (Matson 1974: 346), Spanish moss (*Tillandsia usneoides*) in some early southeastern United States pottery (Simpkins and Allard 1986), and plant biosilica. Organic inclusions have numerous advantages, including their ready availability, making manufacture easy. In addition, because they increase green strength and are eliminated by oxidization during firing, they result in lighter-weight vessels that are easy to transport (Schiffer and Skibo 1987; Skibo 2013: 42; Skibo et al. 1989). Fiber tempering is particularly common in early softwares and low-fired pottery the world over.

Charcoal is a relatively unusual temper constituent, but it has been identified in pottery from throughout the world, including South America (Evans and Meggers 1962), Florida (Wallis et al. 2011), and the Caribbean (Hoffman 1982). In northeastern Florida, identification of the wood species revealed that most was pine, a common fuel; other woods (e.g., sassafras) may have represented detritus from making tools or other uses (Wallis et al. 2011: 2920–22). The charcoal was incorporated into the clay as a result of gathering up domestic hearth materials (including bone) and crushing it for temper. Charcoal and other

plant and organic inclusions also have the advantage of being datable by AMS radiocarbon assay (Boaretto et al. 2009; Derevianko et al. 2004; Higham et al. 2010; Kuzmin et al. 1997; Orton et al. 1993: 19).

Dung from various animals, usually domesticated—rabbit, donkey, horse, cattle—may be added to clay and commonly consists primarily of plant material (Bowen and Moser 1968: 92–95; London 1981). Other animal products added to clays include bird droppings in hunter-gatherer pottery in Karelia (far northwestern Russia; German 2010: 261) and blood in arctic North America (Stimmell and Stromberg 1986: 248). These very fine organic substances increase plasticity and perhaps also adhesiveness through the presence of gel-forming hydrated organic polymers (London 1981: 193).

Material of human manufacture is also used as temper, including slag from copper smelting (Martin et al. 2013). More commonly the material is ground potsherds or brick, referred to as grog. In Southeast Asia, potters prepare grog temper "from scratch" by mixing clay with rice chaff, firing it, and then crushing the material into small bits to use in making vessels (Solheim 1965: 259). Grog temper in northern Cameroon signifies renewal of life cycles (Gosselain 1998: 101). In tropical eastern Peru, the availability of ancient sherds to be ground up for temper is an important factor for Shipibo-Conibo potters in deciding where to settle (DeBoer and Lathrap 1979: 111). The Shipibo-Conibo manufacture jars and bowls from a complex set of "recipes" prescribing specific mixtures of three clays (black, red, and white) and three tempers (*caraipé* or plant silica, grog, and sometimes wood ash):

> the ways in which different clays and tempers are mixed depends on the kind of vessel to be made. Non-cooking ware . . . is ideally made from a mixture of equal parts of white and red clay tempered with two parts crushed sherd to one part *caraipé.* Cooking ware follows a more complicated recipe. In *ollas,* black clay tempered with two parts *caraipé* to one part crushed sherd is ideally used for the base and body of the vessel, while the neck is made from red clay tempered with reversed proportions of *caraipé* and sherd.
>
> *(DeBoer and Lathrap 1979: 110–11, 116–17)*

Lumps of dried clay occasionally have been noted in descriptions of "clay-tempered" pastes (see Porter 1964; Shepard 1964; Weaver 1963; Whitbread 1986). However, these are likely to be small subrounded crumbs of dried clay unintentionally incorporated into the mass (for example, during wedging) but never thoroughly wetted, thus remaining distinct.

4.2.2 Problems in Terminology

Dictionary definitions consider the word temper to be both a noun and a verb, although as a noun its most common senses refer to human feelings or temperament. Etymologically, the verb is traced to late Old English *temprian* "to bring to a proper or suitable state, to modify some excessive quality, to restrain within due limits." This in turn is traced to Latin *temperare* "to mix correctly, moderate, regulate, blend," usually in a temporal sense (*Online Etymology Dictionary*). Archaeologists, too, use "temper" as both a noun and a verb. As a noun it typically refers to the coarser non-clay components in a clay paste assumed to have been added by potters to modify the properties of the clay; it is similar to words modern studio or commercial ceramists use for added particulate matter, which may be called grog or filler (Brody 1979: 7–8). As a verb, temper refers to the action of adding that material.

For archaeologists, problems in the proper use of the term temper have arisen for several reasons. One problem focuses on identification of the material, which is usually based on size and visibility. In examining a fired sherd or vessel, only relatively coarse inclusions—for example, those visible in a 10x hand lens—are clearly identifiable as materials that likely modified the properties of a clay paste. But many additions to clays leave little to no readily visible trace in the fired sherd and so are effectively excluded from discussions of temper constituents, although they modify the original clay's workability, drying, firing, and use-related properties. Organics or salt added to the clay might be visible only as "negative" inclusions—as casts or voids—after firing. In the strictest sense, the water added to make the dry clay plastic (Phelps and McGuire 1956; Rye 1976: 121–23) can be considered a tempering agent. This is particularly true if the liquid is salt water, the salt modifiying the effects of decomposition of calcite.

A second difficulty is behavioral and concerns how the particles came to be present in the clay. The definition of temper suggests that potters intentionally added these substances to modify the properties of the clay when wet or dry. In commercial pottery, and in traditionally made products today, the addition of materials as temper is empirically verifiable. But much of what is called temper in the archaeological literature may designate constituents naturally present in the original clay material, rather than added. Potters may have purposefully selected the clay to take advantage of this "natural temper."

Third, setting aside for a moment the question whether the clasts were naturally present in the clay deposit, the notion of temper has an implicit quantitative sense—that whatever it is, it is present in amounts sufficient to affect the clay's properties. Small quantities of material may have been incorporated accidentally while processing (grinding, soaking, wedging) the clay for manufacture, such as bits of dried clay. Although even these small amounts may sometimes be characteristic of a particular paste (Shepard 1936: 438), they are not temper in the sense of being intentional additions sufficient to modify the clay properties.

A final concern is determining what constitutes *un*tempered pottery. As noted, pottery may incorporate appreciable quantities of inclusions that are naturally present rather than added by the potter. Behaviorally, this is untempered clay, although technically and functionally the inclusions modify the properties of the clay mineral component. On the other hand, fine paste pottery materials are often spoken of as untempered because they have few visible clasts. Yet these may contain abundant natural (but fine) non-clay particles. Or they may be mixtures of two clays, one or neither having coarse particles; in this case the mixing itself is an act of tempering.

Given the problems and ambiguity of the term temper, several alternatives have been recommended, such as aplastic (March 1934: 16) and "*nonplastic* . . . in a general sense and for material of indeterminate source" (Shepard 1976: 25). Aplastic and nonplastic avoid the issue of whether the substance was deliberately added (temper sensu stricto) or was naturally present. However, these terms do not accommodate the possibility that the added materials were themselves plastic (i.e., other clays) or that they enhanced plasticity (e.g., fine organics), and the expressed contrast with "plastic" constituents suggests the opposite. Dean Arnold (1974: 45) suggested redefining or abandoning the term temper, preferring more correct if somewhat cumbersome descriptions such as clay "modified by the potter

using . . .” versus “naturally occurring nonplastics.” Among French and Spanish speakers, the term *degraissant* or *desgrasante* (lit. degreaser; see Balfet et al. 1983: 51) calls attention to one of the functions of temper, reducing the clay’s fatness or stickiness, but this is not its sole function.

Terms such as additive, aggregate, binder, filler, grog, modifier, and opening material are perhaps more common among studio or commercial ceramists than among archaeologists, and obviously all of these refer to deliberate additions rather than to materials occurring naturally in the clay (Bennett 1974: 81–82; Norton 1970: 96, 99). Binder refers to organic materials added for workability and green strength. The term grog has a special usage among archaeologists and ceramists alike; meaning crushed, prefired and “pre-reacted” clay materials such as potsherds or brick, it therefore refers to one kind of temper, and not to the generic or functional material itself. Opening material has been suggested to emphasize the function of inclusions—that is, their role in increasing porosity so as to facilitate even drying, firing, and thermal shock resistance (Woods 1986: 170).

Another suggestion is the term inclusion (see Rye 1981: 31–32). Most nonchemical characterization analyses of pottery directed toward what is commonly called temper focus on identifying particulate constituents larger than clay-size. These particles may be mineral or organic, large or small, plastic or nonplastic. The term inclusion explicitly avoids dealing with how these components got into the clay. They may be present in the natural clay selected by the potter or additions to it; if added, the term is neutral on whether the incorporation was intentional.

For these reasons inclusions is a more appropriate term than temper in studies of the pastes of archaeological pottery, covering virtually all circumstances except the mixing of two (or more) clay substances to form the paste. Temper is best restricted to definitely added substances (Shepard 1976: 25).

4.3 Distinguishing Naturally Present from Added Constituents

The critical distinction between deliberately added (to modify the clay properties) and naturally present materials can be problematic. Four characteristics are usually considered in addressing this issue: the identity of the substance(s) and the particle shape, size range, and amount (see Stoltman 2001: 301–5).

4.3.1 Inorganics vs. Organics

The primary categories of inclusions that can be assumed, with varying degrees of confidence, to be added to clays rather than occurring naturally are grog (angular fragments of crushed fired clay), quantities of volcanics, and many kinds of vegetal matter. Volcanics or tephra—ash, sand, crushed pumice—may be naturally present in sedimentary clay deposits, although typically in small amounts because this material is finely particulate and decomposes. Vegetal matter may or may not be a natural constituent. Organics typically have been burned out of a fired clay object and are identified instead by their casts and the considerable pore space they leave in the fabric. Domesticated plant materials (e.g., wheat chaff) are almost certainly added, but rootlets and other detritus might be naturally occurring in a recently exposed or near-surface deposit.

Like quartz and calcite sand, mica, shell, and sponge spicules often occur naturally and abundantly in clay deposits, depending on their formation processes. Mica—both biotite and muscovite—is not uncommon in pottery, but because it is a common constituent of clayey sediments it is not likely to have been added as temper unless the particle sizes and quantities are large. Mica may remain in primary clays after weathering from a parent rock, and at times might be present in considerable amounts. When mica is abundant in pottery, it is likely that the vessels were made from a micaceous clay or clay tempered with crushed micaceous rock (e.g., a schist) rather than being tempered with mica alone (Shepard 1976: 162).

With respect to shell, although small amounts of whole or broken shells of terrestrial or freshwater snails, mollusks, or foraminifera may be present in sedimentary clays or littoral sands, in most cases where shell is added as temper it is present in relatively large quantities (ca. 20–30%). In highly acid environments the shell might be leached out, leaving platy voids.

Biosilica may be present in pottery as microfossils from either plant or animal sources and occurs as both natural constituents and added temper (see Quinn and Day 2007). Plant sources of biosilica are usually phytoliths from trees or grasses (Rapp and Mulholland 1992), which may be freed for use by burning the plant. The presence of phytoliths in certain pottery pastes proved useful in analyses of Classic Maya pottery at Palenque, distinguishing wares produced on a grassy plain from those in the mountains to the south (Rands and Bishop 1980).

Animal microfossils, such as diatoms and sponge spicules, are particularly common in freshwater or marine sedimentary clays. Diatoms, with their unusually shaped exoskeletons, have proven useful in identifying clay source regions (see Battarbee 1988; Juggins and Cameron 1999; Mannion 2007; Matiskainen and Alhonen 1984; Wallis et al. 2014; but see cautions by Kligman and Calderari 2012). Spicules, tiny rods that formed the skeletons of sponges, are common in pottery of Florida and the Southeastern United States (Borremans and Shaak 1986; Saunders and Hays 2004) and also have been noted in Mali (McIntosh and MacDonald 1989) and Amazonian South America (Linné 1957: 156). Sea urchin spicules are also present in the calcareous clay from the Guadalquivir River banks, used in Sevillian majolica pottery production (Magetti et al. 1984: 159, fig. 3). The sharp, acicular shape of these spicules, like that of crushed pumice, contributes to the light weight and green strength of a piece.

4.3.2 Size and Shape

For mineral inclusions, the shape of the particles can give clues to the depositional origin of the clays and hence to the inclusions' origin. Pronounced angularity of the grains is interpreted as meaning a rock was crushed (e.g., "grit") and hence that the mineral was added. Rounding or sphericity (fig. 4.4), on the other hand, is often interpreted in terms of abrasion from wind, stream, or wave action during transport of the grains accumulated in a sedimentary clay deposit. More specifically, granulometry —consideration of the range of sizes and shapes, and their distribution in the ceramic, of individual mineral constituents—is informative. For example, a clear division in the frequency distribution of coarse (and angular) fragments versus small (and rounded) particle sizes may suggest that the coarse, angular particles were added to a fine sandy clay. On the other hand, if all particles are in the very fine sand-to-silt size range, it is more likely that they were naturally present in the clay deposit.

Such considerations are useful with respect to questions concerning quartz inclusions in pottery, which are particularly intractable in areas of sandy soils. In these areas, clay deposits are likely to have a considerable admixture of quartz sand, and sand is also likely to be one of the most available tempering agents. Similarly, the distinction between marly clays and carbonates as temper is based on both quantity and shape: particles in calcareous sedimentary clays will be rounded from the action of transport and deposit and are usually rather fine-grained because the mineral readily fractures along cleavage planes. The addition of crushed limestone or dolomite should be apparent in larger sizes and angularity. This distinction cannot always be maintained, however, because subangular particles may be present in primary clays or in sedimentary clays deposited relatively close to a parent material.

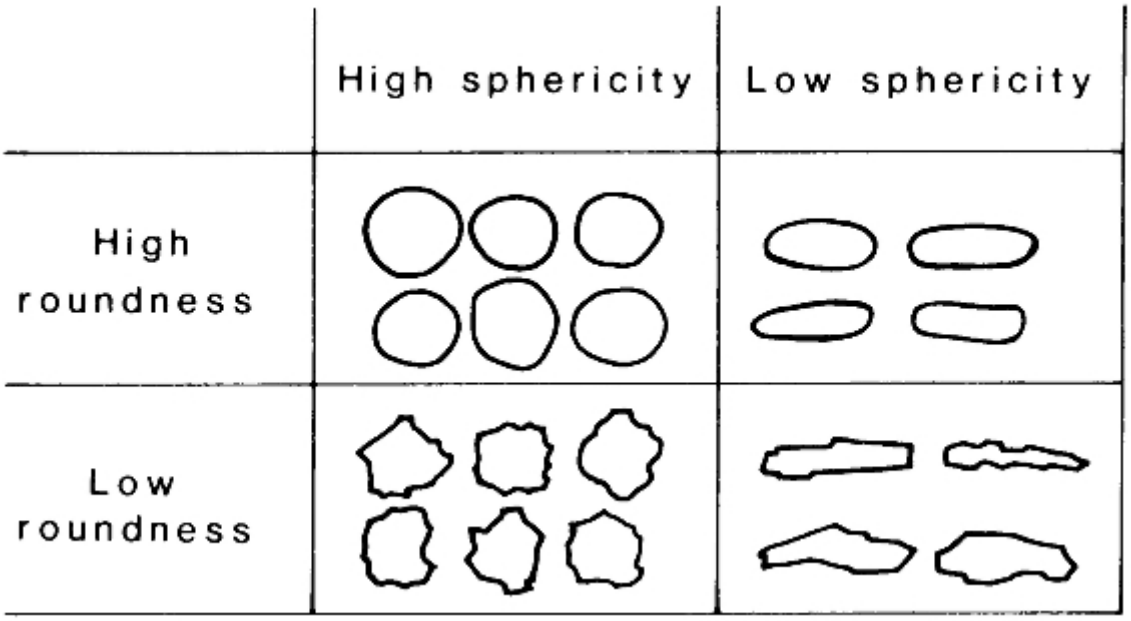

Figure 4.4 Relation between high and low sphericity and roundness (angularity) of grains.

More broadly, it was proposed that temper consists of all inclusions in the ceramic with a diameter greater than 0.015 mm (Magetti 1982: 122). These materials may be differentiated into artificial temper (if "added artificially") or "natural temper" (an oxymoron) if originally present in the clay. It might be noted, however, that this particle size is within the silt range in most classifications (see fig. 2.2), and one could question to what extent ancient, non-industrial potters' additions would be so finely powdered and sorted. A diameter of 0.05 mm might be more appropriate, but it is questionable whether such firm boundaries are of any value at all.

A good natural clay for pottery ideally should have inclusions that are angular or acicular (e.g., crushed pumice, sponge spicules) and present in a range of sizes. In such a deposit the smaller particles and the clay itself bond and interlock with the angles and edges of the inclusions, conferring strength in both dry and fired states. But all these observations are guidelines, and in some circumstances it will be impossible to distinguish between natural and added inclusions in a sherd. Although studies of archaeological pottery focus on the cultural aspects (potters' behavior and decisions in fabrication and use), it is important to recognize the distinction between characterizing a material and drawing behavioral inferences from that characterization. In its traditional meaning, temper is a behavioral inference drawn from an analytical observation, not the observation itself, and this suggests that the term should be used very carefully to refer to particulate matter in the paste of archaeological pottery.

Defining temper is more than a semantic quibble, because the deliberate combining of raw materials into a pottery paste has significant technological, functional, stylistic, and cultural implications for the pottery-making process and for the uses of the products

(see Shepard 1964). For example, the ceramic classificatory units that archaeologists create, often based on inclusions, are presumed to have chronological, ethno-political, spatial, social, and functional significance. They represent the traditional foundation for regional historical sequences and outlines of cultural interactions. More important, the choice of tempering materials is assumed to represent a consistent or normative pattern, and thus the regular covariation of particular tempering agents with particular vessel forms or styles is seen as culture-specific. For these kinds of culture-history reconstructions, it is in some senses immaterial how the inclusions came to be in the clay, whether the potter selected clay with particular kinds of constituents already present or added them to the clay. The observable fact of covariation exists regardless of the behavior involved.

Box 4.2 Natural vs. Added Inclusions

Identifying added matter in pottery begins with recognizing that many materials—inorganic and organic—can occur naturally in clays, either as residues of the parent rock in primary clays or as particles incorporated during transportation and rebedding of sedimentary clays. It is useful to have some knowledge of the natural environment in the vicinity of the archaeological recovery location of the pottery of interest—for example, reviewing geological and vegetation surveys and maps, as well as obtaining samples of local clays—to develop a picture of available resources for pottery making.

The major criteria for determining whether large inclusions were likely added as temper, size and shape, can be assessed with a 10X loupe. For smaller particles, size and shape range are best observed in thin section. Microscopic analyses provide qualitative and quantitative data on what constituents are present and in what amounts, sizes, and shapes. This information, supplemented by additional data from geology or ceramic science—such as suites of minerals, particularly accessory minerals, representing particular rock sources—permits inferences about cultural significance, such as whether certain component phases of the pottery are inclusions added to the paste, whether they have plastic properties, and what effects they would have had on workability, drying, firing, and use. After such determinations, it is possible to assess the likelihood that these materials were deliberately added by the potter to temper the clay. Petrographic thin sections are also informative on firing conditions and postdepositional alteration. In the case of whole vessels, such as museum specimens, thin-sectioning is usually not possible. However, X-ray radiography can be a useful technique for quantitative assessments of temper size and shape, as well as other observations about manufacture such as forming technique and porosity (Alexander and Johnston 1982; Berg 2008; Braun 1982; Foster 1985; Pierret et al. 1996; Rye 1977; Vandiver and Tumosa 1995).

On the other hand, for many questions about pottery production and use, understanding tempering behavior is critical. For example, associations among paste, temper, form, and style may permit some provenience determinations, both distinguishing local from intrusive tradewares and locating specific source materials. It also is important in relating groups of unknown sherds to known kiln materials or raw resources, and to the history of manufacturing technology. Finally, the kinds, sizes, and shapes of tempering materials are important in determining pottery functions and performance characteristics: pottery with different functions may have distinct tempers, as in some Southwestern pottery (Shepard 1939: 277–81; Stoltman 2001: 310–11).

5 Drying and Shrinkage

> Merely to handle a raw, dried pot properly and to get it into the kiln requires some feeling of tenderness toward it.
>
> Rhodes 1973: xviii

After a clay/water mass is formed into a desired shape, it is allowed to dry, a process that may take several days or even weeks. It can be a dangerous step, because if a formed but still wet piece is dried too rapidly or if drying is incomplete, it may develop flaws that can destroy it. These flaws result from stresses that may arise as water films surrounding the clay platelets evaporate and the platelets draw closer together, causing the clay body to shrink (Kingery and Francl 1954; Moore 1961). If the evaporation is uneven or non-uniform, shrinkage also will be uneven, leading to stresses in the clay body. The consequences may be immediately noted in pieces that crack or warp during drying, or the flaws may not be apparent until the piece is fired. For these reasons, drying is usually carefully monitored.

5.1 Kinds of Water

Understanding shrinkage begins—as did understanding plasticity—with the clay/water system. Two kinds of water loss and two kinds of shrinkage occur during air drying: the water lost is both mechanically combined and chemically combined, and the shrinkage may be measured in both linear and volume dimensions. Chemically combined water that is part of a clay's mineral structure is almost never lost in normal low-temperature air-drying; its loss begins with the application of heat and firing, the ultimate dehydration of clays.

Four kinds of water exist in a wetted clay throughout the transition from a plastic to an air-dried state, whether or not the mass has been shaped: shrinkage water, pore water, surface-adsorbed water, and interlayer and crystal lattice water (see Grimshaw 1971: 443–49; Norton 1970: 157–60). These kinds of water are lost in the order given. The relations between loss of this water and volume shrinkage can be envisioned by figures 5.1 and 5.2. These figures are idealized diagrams of a hypothetical clay/water mass during air drying.

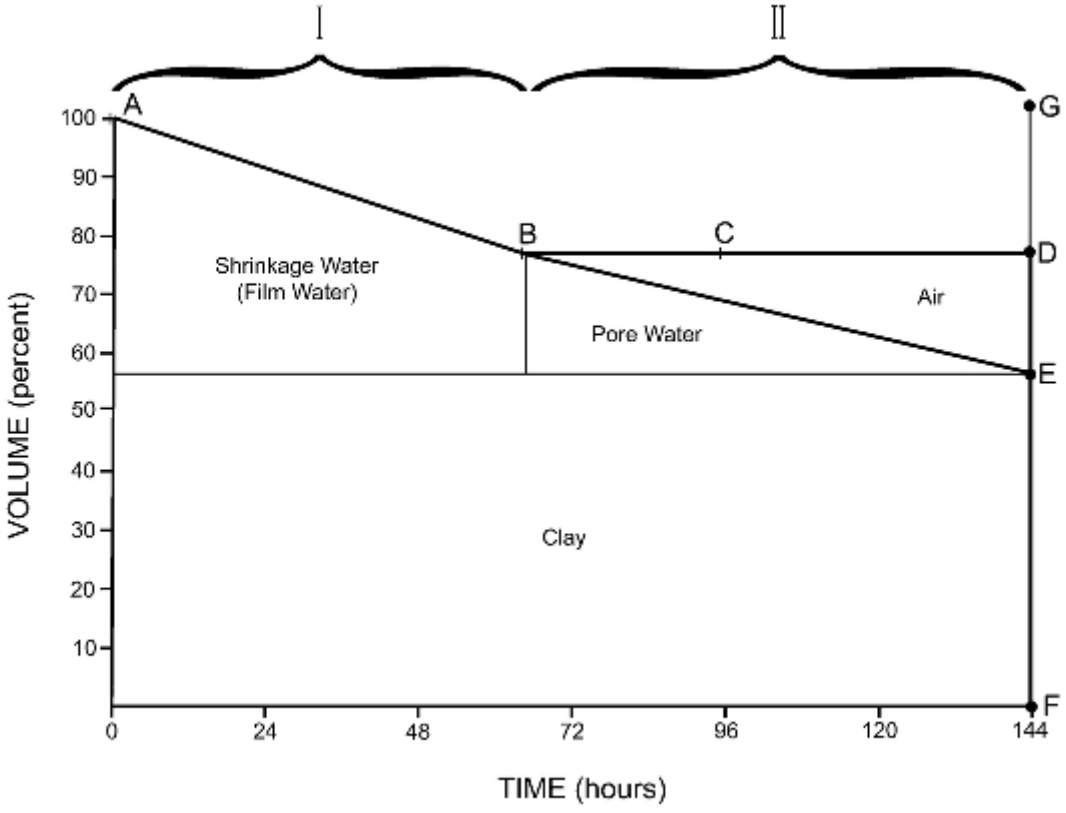

Figure 5.1 Idealized diagram of a hypothetical clay/water mass, showing relative changes in volume of water and pores as it is air-dried. After Salmang 1961: 33 and Norton 1970: fig. 11.2.

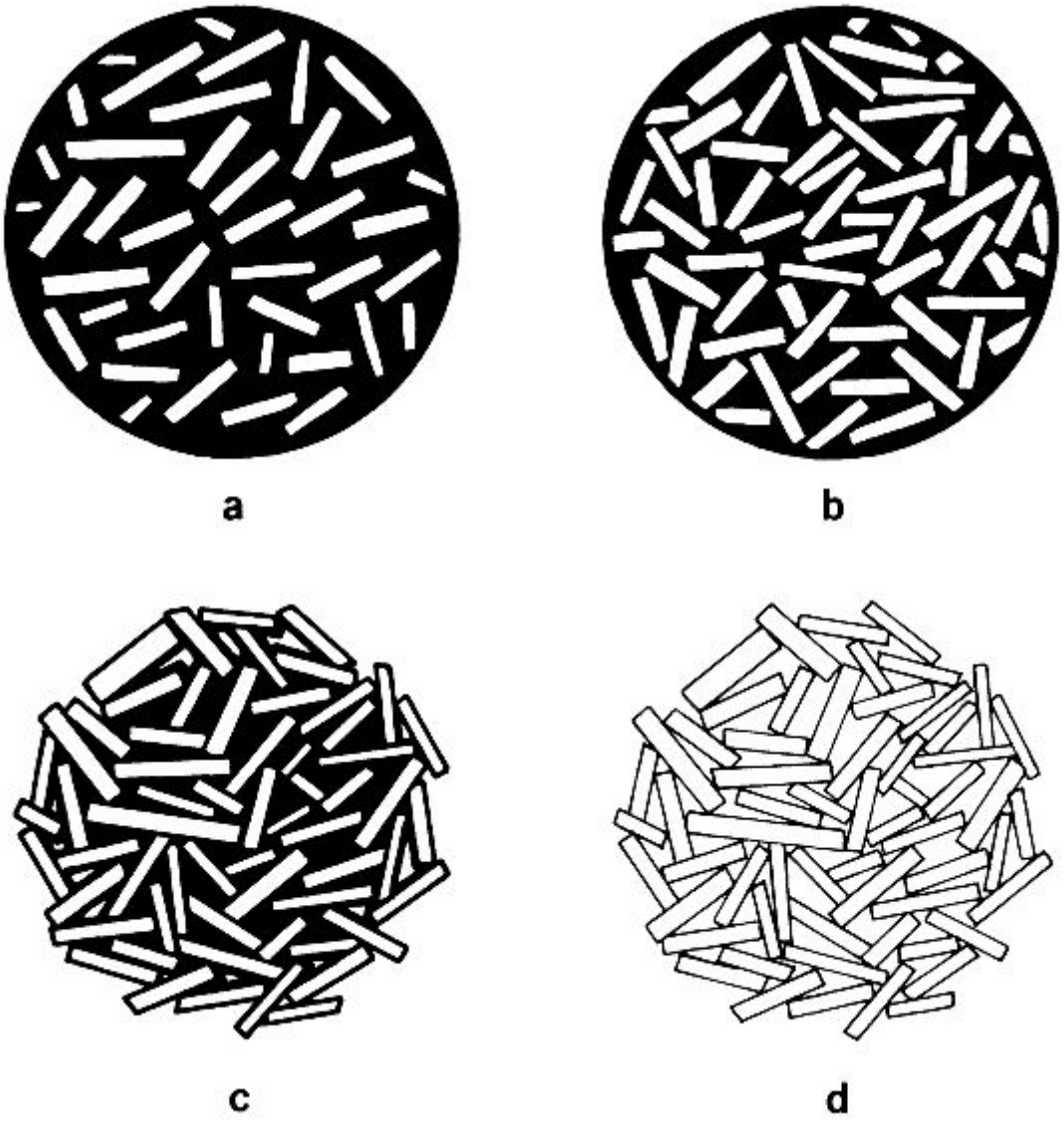

Figure 5.2 Idealized magnified cross-section of water and particle arrangements in a hypothetical clay/water mass during drying. Letters correspond to points on the drying curve in fig. 5.1: *a*, excess free water (shrinkage or film water and pore water) in a plastic clay; *b*, the critical point or leather-hard stage, when particles come into contact and water exists as pore water; *c*, water (as pore water and adsorbed water surrounding clay platelets) evaporates from the center throughout the ends of capillaries; *d*, dry clay. After Grimshaw 1971: fig. IX.7; Lawrence and West 1982: fig. 6–1; Norton 1970: fig. 11.1.

Point A on fig. 5.1 represents such a mass at optimum plasticity, consisting of 55% clay and 45% water by volume (or 75% clay and 25% water by weight), as it is beginning to air-dry. The early stage of drying, indicated by roman numeral I at the top of the figure, is known as the constant-rate period of drying (Grimshaw 1971: 544–45) because volume change and moisture content are linearly related. The first kind of water lost is shrinkage water, which is most of the water that was mechanically combined with the dry clay to develop plasticity. Shrinkage water could also be called film water, for it primarily comprises the films that surround and separate the clay platelets, resulting in a low density of the mass (fig. 5.2*a*); it also acts as a lubricant. As this

shrinkage or film water is removed, the mass contracts and surface tension forces draw the clay particles closer together.

After 48 hours of water loss, the platelets have become more densely packed until finally they are in contact with each other (fig. 5.2*b*). The mass has reached the critical point, Point B on fig. 5.1. At this point, the shrinkage or pore water is eliminated and physical reduction of the clay bulk effectively ceases because the touching particles have creating a rigid framework or skeleton. The original bulk volume has been diminished by 22%. The clay fraction has not changed—it is still 55% of the original volume—but the amount of water has been severely reduced. Water now constitutes only 12% of the bulk, compared with 45% at the start.

At Point B, then, all air-temperature shrinkage has been accomplished, the particles are in contact, plasticity has been lost, and the clay has attained the leather-hard stage. A formed clay piece can be carefully handled, because the clay is rigid. Beyond this point, this framework cannot be significantly reduced in size, even when the remaining water in the pores between the platelets is removed by room-temperature or low-heat (105–110°C) drying. Further appreciable shrinkage takes place only in firing.

The water remaining in the system at critical point B is termed the critical moisture content. It consists of the pore water, the remainder of the mechanically combined water added to make the clay plastic, plus lattice and perhaps interlayer water, depending on the clay mineral(s). Pore water may compose 10–26% of the true volume of the clay body, depending on particle size; fine clays have more pores and thus more pore water. Loosely held in the clay, pore water is easily given up to the air, but after shrinkage is complete the pores are very small, so the water takes longer to move outward from the interior.

Drying beyond point B, after a leather-hard state has been attained (stage II), is thus slower than during evaporation of shrinkage water (compare the slope of AB with that of BE) but less pore water exists to be lost. Because the lost pore water is replaced by air and pore water does not surround and separate the clay platelets, which are now touching, the weight of the clay will continue to decrease, but only the true volume will be reduced, not the bulk volume (point C on fig. 5.1; also fig. 5.2*c*).

Surface-adsorbed water is adsorbed from the atmosphere by the surface of a dried or drying clay mass. It is not the same as water adsorbed onto the surfaces of individual clay platelets, which enables plasticity. A dry clay, and even a drying clay that appears to have a dry exterior, actually holds a microscopic film of water on its surface. This film represents an equilibrium between the water vapor pressure of the clay and that of the atmosphere, although it may penetrate capillaries from the surface. Only one molecule thick, this adsorbed water is not included in volume loss, weight loss, or shrinkage calculations.

Finally, interlayer water exists between the unit layers of the 2:1 or three-layer clay minerals (such as smectites; see fig. 2.7). Because it occurs only in these minerals, the contribution of interlayer water to drying shrinkage is usually negligible. This water is

strongly held because it is part of the internal structure of the clay platelets, and it is the last water lost in drying. Crystal lattice water is the chemically combined water held as hydroxyls (OH^-) within the layer structure of the clay minerals. This is the water that makes clays "hydrous" alumina silicates. Lattice water (or water of hydration) is lost only by heating beyond 110°C, usually to the range of 450–600°C.

Returning to fig. 5.1, at point D (fig. 5.2*d*), after 144 hours of drying, all water except chemically combined (lattice) water is lost. Line DF on the figure represents the bulk volume of the dry clay, or the clay particles plus air in the pore spaces. Line EF represents the true volume of the clay itself, which has remained unchanged from the original mass (and retains lattice and interlayer water). Line DE represents the volume of pores in the clay; these are occupied by air and do not contribute to the true volume, only to the bulk volume. Line GD represents the percentage shrinkage.

During drying, water is lost by capillary action, or movement through the clay pores from the interior to the exterior of the body. Drying begins at the surfaces and edges of the clay piece, as water is continuously drawn outward to the surface where it evaporates. Two mechanisms are at work. One is a moisture gradient within the clay, which forces water flow from the moist interior to the drier surfaces. The second is a pressure gradient within the capillaries, between the outer vapor pressure and the interior liquid, which forces water from the filled interior capillaries into the exterior ones, which are emptying.

The role of capillary flow becomes clearer when the drying process in a coarse clay is compared with that in a fine clay. In extremely fine clays, drying is hindered by the very characteristic that makes them desirably plastic: fine particle size. To develop plasticity more water is needed to cover the extensive surface area of the platelets, and the water exists in a more extensive network of finer capillaries than in a coarse clay. The water movement, hence drying, is slow.

5.2 Green Strength

Resistance to cracking and warping as a clay body dries is a function of its strength in the dried but unfired state, known as dry strength or green strength (Holdridge 1952; McDowell and Vose 1952; Pask 1953; Ryan 1965). A dried body with considerable green strength has significant integrity resulting from the forces bonding the clay platelets together; it is resistant to cracking and warping. The attributes that enhance green strength include fine rather than coarse particle size (Table 5.2), the presence of Na^+ ions, and a deflocculated state. Organic matter may be added to a clay to increase its green strength; examples are flour, cornstarch, milk solids (casein), and gums of various trees and bushes (Norton 1970: 99).

Box 5.1 Measuring Drying Shrinkage

The shrinkage of a plastic clay caused by loss of mechanically combined (pore or film) water during air-drying or low heat drying can be measured as linear drying (or air) shrinkage or volume drying (air) shrinkage. Linear drying shrinkage (%LDS) is computed by marking wet clay with lines a specified distance apart, completely drying the clay at 105°C, re-measuring the distance, and subtracting it from the original measurement. The result is divided by the wet length measurement and converted to a percentage:

$$\%\mathrm{LDS} = \frac{\mathrm{length}_{\mathrm{wet}} - \mathrm{length}_{\mathrm{dry}}}{\mathrm{length}_{\mathrm{wet}}} \times 100$$

Volume air or drying shrinkage (%VDS) is computed by measuring the volume of the thoroughly dried clay piece in a volumeter filled with kerosene. The piece is then removed, dried, and soaked for twelve hours in kerosene of the same specific gravity as that used in the volumeter, after which its volume is again measured in the volumeter. The formula is as follows:

$$\%\mathrm{VDS} = \frac{\mathrm{volume}_{\mathrm{wet}} - \mathrm{volume}_{\mathrm{dry}}}{\mathrm{volume}_{\mathrm{wet}}} \times 100$$

Table 5.1 compares some linear and volume drying shrinkage measurements for several clays. For a uniform, isotropic body, %VDS = 3%LDS if the shrinkage is small; inhomogeneous shrinkage or large shrinkage values will cause deviations from this general relationship.

Table 5.1 Ranges in Air-Drying Shrinkage for Several Clays

Clay	%LDS	%VDS
Crude kaolin	5.00–7.60	14.11–20.92
Ball clay	5.25–12.00	21.90–31.92
Refractory clay	4.25–11.00	30.48–45.00
Stoneware clay	4.80–9.30	15.11–41.20
Flint fireclay	0.78–6.59	2.36–21.12
White sedimentary kaolin	4.50–12.50	7.53–36.46
Saggar clays	2.80–10.80	9.10–25.00

Source: After Ries 1927: 227.
Note: LDS, linear drying shrinkage; VDS, volume drying shrinkage.

Green strength increases as moisture is lost during drying, as in fig. 5.1. Strength is greatest in completely dry bodies, whereas ware that is only leather-hard is more susceptible to deformation. The cause of this is not fully known; it has been attributed to variations in the weak electrostatic attraction between molecules known as van der Waals forces, which in this case hold the clay mineral layers and particles together.

Table 5.2 Comparative Green Strength (psi) of Clays with and without Sand

	Dried Clay			Dried Clay Plus 50% Sand		
Clay Type	**Compressive Strength**	**Tensile Strength**	**Transverse Strength**	**Compressive Strength**	**Tensile Strength**	**Transverse Strength**
Ball clays	565–1148	135–210	375–558	464–777	124–180	242–330
Plastic clays	631–954	155–172	484–520	476–553	113–150	216–280
Plastic kaolins	455–539	104–147	239–325	286–559	54–110	122–210
Primary kaolins	205–349	34–69	74–166	164–172	29–35	56–82

Source: After Ries 1927: 221.

5.3 Drying Defects and Causes

During drying, the movement of water through the clay and its loss by evaporation not only bring about shrinkage, they can also cause stresses leading to defects such as cracking or deformation. Many variables contribute to problems in drying, including clay particle size, presence of preferred orientation, amount of water present, and the ambient environment. All of these are most serious during the early stage of drying, before leather-hardness is reached.

5.3.1 Particle Size and Shape

Clay particle size, particularly an abundance of fine particles, presents many opportunities for defects to occur: the proportion of water is large, the process is slow, shrinkage is high, and water may evaporate from the surface faster than it can be resupplied from the interior. The surface will then shrink more rapidly than capillary movement through the interior pores can accommodate, creating a strong moisture gradient. The resultant stresses of the shrunken surfaces compressing over the interior may cause warping or cracking. Though visible warping and cracks are clear indications of structural defects in a dried product, the cracks are often invisible and the damage may become apparent only after they are accentuated by the additional shrinkage that occurs during firing.

A further problem with extremely fine clays is that, if they are sedimentary and highly organic, the water in the pores may contain dissolved or dispersed matter such as salts or organic colloids. As water is drawn from the interior, these salts and minute organic particles also flow to the surface, where they may form a residue or scum that can change the density, color, or hardness of the piece (see Brownell 1949). Colloidal clay particles also may migrate in this fashion, affecting the density and hardness of the surface and causing fine surface cracks from compressive stresses during drying. One way to lessen the risk of warping and cracking of products formed from fine clays is to allow them to dry very slowly.

Particle shape is important in terms of shrinkage, drying, and strength of an unfired or fired clay body. In principle, a clay mass will shrink less and dry more easily if all grains are spherical, uniform in size, and closely packed. Such a state rarely exists, however, except perhaps in very well-sorted, highly abraded wind- or waterborne sediments. Indeed, for pottery such characteristics are undesirable, because the rounded surfaces do not develop the strong interlocking particle frameworks typical of platelet shapes, and may lead to a weak body.

5.3.2 Method of Shaping

The method of shaping a clay body can lead to anisotropic shrinkage: different rates of shrinkage along two directions of measurement. This anisotropy has two common causes in forming operations. One cause is varying alignments of particles. This may occur in parts of a vessel where the orientation of the clay platelets—and wall thickness—changes sharply, such as at corners, seams, and angles.

Another cause of uneven shrinkage is "differential water": varying proportions of water and clay particles in different parts of the finished object. For example, areas that are repeatedly stroked and smoothed during forming generally are wetter than other parts; similarly, on a pot thrown on a wheel the exterior will be wetter than the interior and the base wetter than the upper portion. The portion of the body containing more water will shrink more than the drier portion, causing stresses that can lead to warping or cracking (fig. 5.3).

5.3.3 Preferred Orientation

Another factor involved in anisotropic shrinkage is called preferred orientation of the clay particles: nonrandom or directional positioning in which the platelets become oriented parallel to each other like courses of brickwork, rather than occurring randomly or in a face-to-edge arrangement. Preferred orientation is more easily observed in clay minerals with relatively larger particle sizes and also in clay bodies with flat, platy inclusions, such as micas or crushed shell, which may make the body laminated or fissile. Although strong and well bonded across the laminae, the body will be weak along the linear orientation of the plates and may crumble in layers. Clay materials with little range in particle size may be extremely weak and lack green strength.

Shrinkage occurs differentially according to the direction of orientation for two main reasons: the varying volumes occupied by water films versus clay platelets in each linear dimension, and the variable densities of particle packing after shrinkage water is lost (fig. 5.4). Shrinkage will be greatest perpendicular to the orientation of the platelets, because more water films occur per unit area in that direction. Shrinkage will be least in the direction parallel to the particles. Because of this uneven shrinkage in all directions of the clay mass, the final product may warp or crack if the tensions exceed the strength of the dry clay body (e.g., fig. 5.4*c*).

Figure 5.3 An S-shaped crack on the base of a small wheel-thrown ashtray, a typical drying defect (exaggerated in firing) caused by differential water and resultant uneven shrinkage.

Preferred orientation may be caused to varying degrees by virtually all operations of forming a clay body (extruding, coiling, throwing, drawing), because all involve repetitive stroking of the clay. Hand pressure is sufficient to realign clay particles "floating" in their water films with their long dimension parallel to the forming pressure. The light pressure used in burnishing a clay surface also may reposition particles, and the luster of the burnished area is a consequence of preferred orientation as well as compaction of the very finest particles brought to the surfaces. Preferred orientation may also be caused by the natural settling behavior of clay particles in a slip, or by the absorptive properties of molds used in slip casting.

Finally, preferred orientation may result from the way particles are dispersed within the clay/water system owing to their electrical charges and the presence of ions. Certain kinds of ions will alter the pH of the system as well as modify the arrangement of the particles, leading to system states that are known as flocculated or deflocculated.

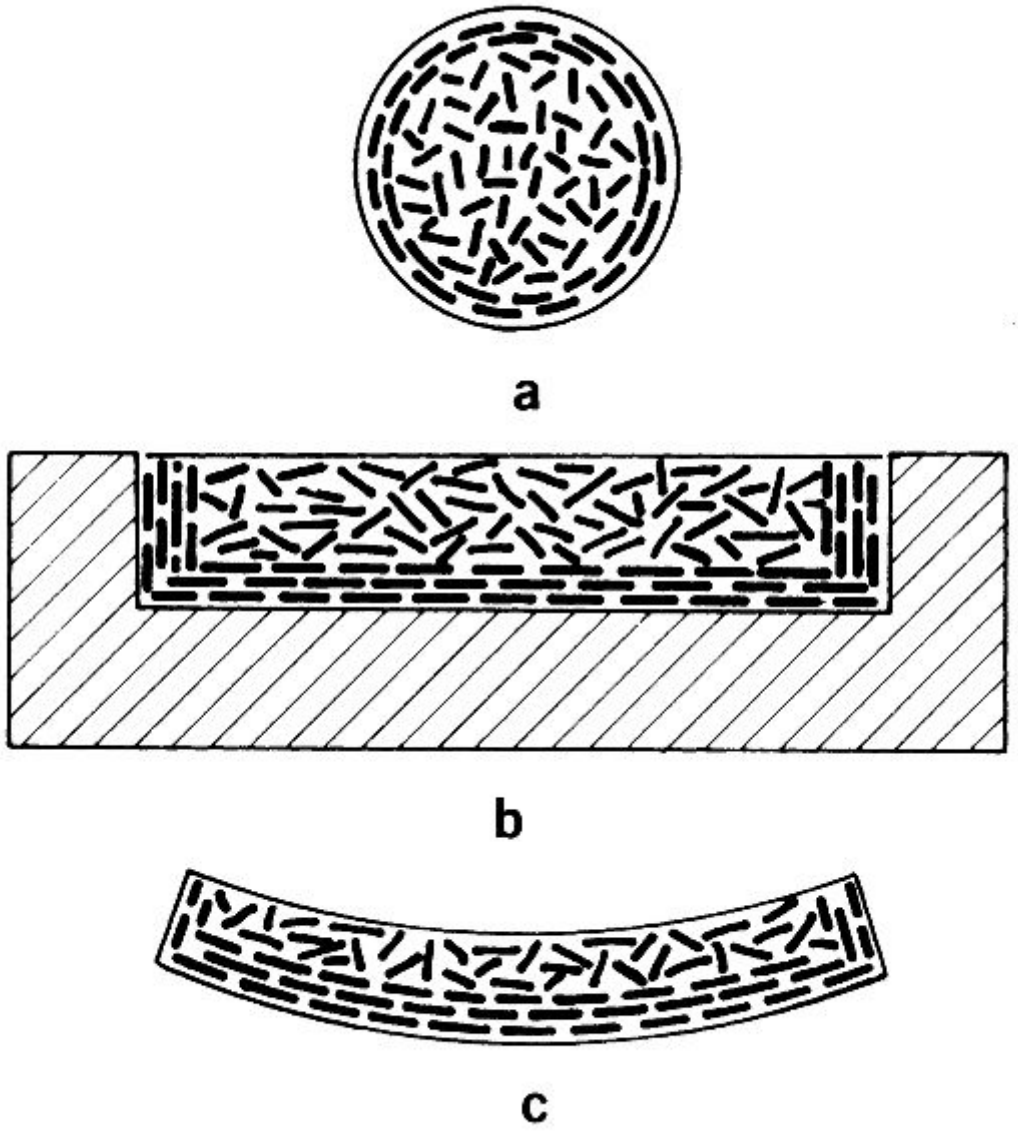

Figure 5.4 Particle-orientation effects: *a*, in a rolled cylinder of clay; *b*, in a slip-cast piece; *c*, warpage of slip-cast piece during drying. Sources: *a*, after Norton 1970: fig. 10.11; *b*, after Lawrence and West 1982: fig. 64*a*; *c*, after Lawrence and West 1982: fig. 64*b*.

5.3.4 Ambient Conditions

Conditions of the drying atmosphere—temperature, humidity, and presence of air currents—are perhaps the greatest contributors to non-uniform drying leading to defects and loss of strength in a clay body. Evaporation and shrinkage are more rapid on external surfaces exposed to the air, which is particularly a problem if pieces are set to dry in an area subject to fluctuating temperatures, humidity levels, or air movement. Sudden changes in temperature or rate of evaporation may disturb the gradients of moisture between clay surface and interior, causing different rates of drying and precipitating warping, especially during early drying, while the clay retains some plasticity, and especially with fine clays. Vessels constructed of finer and denser pastes

or with thicker walls usually must be dried more carefully and slowly, and they may be placed in the shade for all or part of the time.

Placing newly formed clay pieces in sunlight facilitates rapid drying, because heat enables water to migrate through the pores to the surfaces of the piece more easily. In addition, heated air can absorb more moisture from the ceramic than can cooler air. But the heat may also cause more rapid surface evaporation than can be accommodated by internal water movement and the strength of the wet clay object, and this may give rise to defects.

5.4 Preheating

Heating both the ceramic body and the air, either artificially or by placing the clay pieces in sunlight, facilitates rapid dehydration. Modern commercial operations may use humidity driers: the ceramic pieces are heated in a humid atmosphere, then drying proceeds by controlled reduction of humidity. Where pottery is fired without kilns, pots are often slightly warmed immediately before firing. This warming helps ensure that all moisture is out of the clay before firing and minimizes thermal stress when the pots are first placed on the fire or the fire is started around them. Preheating is thus at least a partial equivalent of the early “water-smoking” stage of dehydration in commercial ceramic firing.

Although shrinkage of a clay/water mass during drying is unavoidable, defects are not inevitable. Two approaches promote deformation-free dehydration: reducing overall shrinkage and controlling the drying rate. Notwithstanding the dangers of deformation, a major problem of drying in situations of large output is economics. There must be a balance between the delays caused by slow drying for the sake of safety, and the risks of damage if drying is accelerated by heat or air circulation. Defects are more likely during the first part of the drying time, when shrinkage water is lost and the vessel is shrinking in response. During this period drying is best carried out slowly. After shrinkage has stopped and the formed piece has reached the leather-hard stage, drying can be more rapid.

6 Changes in Clays with Heat

> Ceramics is an exciting combination of art, science, painting, and sculpture. . . . It embodies geology, chemistry, physics, artistry, and more than a little alchemy.
>
> Hopper 2009: 247

After plasticity, the second most salient property of clay is its hardening when subjected to heat. Plastic clay begins to lose water on air-drying, and the changes taking place with water loss—such as shrinkage—continue under elevated temperatures. Rising temperatures cause progressive and usually irreversible physical modifications of the clay/water system, to the point that the original mineral structure changes, plasticity is forever lost, and the clay becomes permanently hardened. A fire-hardened clay object is in some senses metamorphosed into an artificial stone.

The changes that occur in a ceramic as it is heated usually take place within a range of temperatures, but the ranges and reaction times vary with particular clay minerals or mixtures. In addition, the kinds and degrees of completion of these transformations are a consequence of complex interactions among the variables of heating and the circumstances in which heat is applied. This chapter outlines the physical, chemical, and mineralogical changes that occur in a clay material as it is heated to temperatures of ~1400°C. These changes are examined in terms of increasing temperatures of firing and the contributions of individual components of the clay body.

6.1 Variables: Time, Temperature, and Atmosphere

Clays are substantially altered with the application of heat, beginning at relatively low temperatures and continuing through very high temperatures. These transformations are functions of three primary variables of pyrotechnology: time, temperature, and atmosphere. In contemplating the heating or firing of any ceramic these variables must always be considered together. It is inappropriate and insufficient to discuss (or infer) the firing technology of any ancient piece by estimating temperature alone. The duration of firing and the atmosphere in which both heating and cooling occurred are also significant and should not be ignored.

The atmosphere of firing refers to the presence of gases, particularly oxygen, around the clay while heat is applied and allowed to dissipate. Where there is free air circulation and ample free oxygen to bind with elements (ions) on or in the clays, the atmosphere is said to be oxidizing. A reducing atmosphere lacks free oxygen and is frequently, although not always, smoky. Some gases in the firing atmosphere are simply those present in the earth's atmosphere, such as nitrogen and oxygen. Others result from combustion, including water vapor, carbon dioxide, and sulfurous gases (SO_2) escaping from burning fuel; carbon monoxide results from an atmosphere lacking enough oxygen for complete combustion. A third source of gases is the clay material itself, which on heating may emit water vapor, carbon dioxide, or sulfur dioxide, depending upon its inclusions and impurities. The atmosphere of firing affects several aesthetic and use-related properties of the finished product, especially color and hardness, but also porosity and shrinkage. Discussions of and inferences about the firing atmosphere of an article should specify the condition in which the maximum temperature was attained and was held, and the atmosphere during cooling.

The maximum temperature of heating is always a point of interest, but that temperature's significance resides in knowing both its duration (the soaking period) and the atmosphere. Pottery firing temperatures are usually given in degrees Celsius (or centigrade); a conversion chart between Celsius and Fahrenheit is given in table 6.1. An approximate maximum temperature can be assessed through several archaeothermometric techniques based on certain mineralogical and structural changes in the ceramic components. These changes usually occur over a range of temperatures, however, and they are affected by atmosphere and duration. For example, some reactions may be essentially completed, and certain properties may develop, at lower temperatures if the firing atmosphere is reducing rather than oxidizing.

It is particularly important to know how long the ceramic materials were subjected to heat. The total duration of firing includes three periods: rising temperature, sustained maximum temperature or soak, and cooling, when no more fuel is added and the temperature declines to ambient. The kind and degree of completion of the changes that

occur with application of heat depend on how long a given temperature is held. This combined time-temperature variable is known as work heat.

6.2 Changes at Low Temperatures

The changes in a clay body that begin at the lowest temperatures and take the longest time to complete are continuations of the drying process: the movement of water and other materials, chiefly organics, from the interior to the exterior of the piece. These then volatilize and escape into the atmosphere as gases, causing weight loss and shrinkage, although there may be some initial expansion of the clay mineral. The changes are most pronounced at the relatively low temperatures used for terracottas (up to c. 800–900°C), the range at which much unglazed, non–kiln-fired pottery is fired. The loss of water in the clay mineral structure brings about changes in the clay mineral itself and leads to the formation of new minerals characteristic of high-temperature firings.

Table 6.1 Temperature Conversion Chart, Celsius (°C) and Fahrenheit (°F)

°C	*	°F
–17.8	0	32
–15.0	5	41.0
–12.2	10	50.0
–9.4	15	59.0
–6.7	20	68.0
–3.9	25	77.0
–1.1	30	86.0
1.7	35	95.0
4.4	40	104.0
7.2	45	113.0
10.0	50	122.0
15.6	60	140.0
21.1	70	158.0
26.7	80	176.0
32.2	90	194.0
37.8	100	212.0
49	120	248
60	140	284
71	160	320
82	180	356
93	200	392
100	212	413
104	220	428
116	240	464
121	250	482
127	260	500
138	280	536
149	300	572

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2012
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2084
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738	1360	2480
749	1380	2516
760	1400	2552
771	1420	2588
782	1440	2624
788	1450	2642
793	1460	2660
804	1480	2696
816	1500	2732
827	1520	2768
838	1540	2804
843	1550	2822
849	1560	2840
860	1580	2876
871	1600	2912
882	1620	2948
893	1640	2984
899	1650	3002
904	1660	3020
916	1680	3056
927	1700	3092
938	1720	3128
949	1740	3164
954	1750	3182
960	1760	3200
971	1780	3236
982	1800	3272
993	1820	3308
1004	1840	3344
1010	1850	3362
1016	1860	3380
1027	1880	3416

1038
1049
1060
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3956
3992
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4082
4100
4136
4172
4208
4244
4262
4280
4316
4352

1327	2420	4388
1338	2440	4424
1343	2450	4442
1349	2460	4460
1360	2480	4496
1371	2500	4532
1382	2520	4568
1393	2540	4604
1399	2550	4622
1404	2560	4640
1416	2580	4676
1427	2600	4712
1438	2620	4748
1449	2640	4784
1454	2650	4802
1460	2660	4820
1471	2680	4856
1482	2700	4892
1493	2720	4928
1504	2740	4964
1510	2750	4982
1516	2760	5000
1527	2780	5036
1538	2800	5072
1549	2820	5108
1560	2840	5144
1566	2850	5162
1571	2860	5180
1582	2880	5216
1593	2900	5252
1604	2920	5288
1616	2940	5324

1621	2950	5342
1627	2960	5360
1638	2980	5396
1649	3000	5432

Source: After Lawrence and West 1982: app. A-9.
Note: This chart can be used in two ways: (1) Any Celsius temperature in the left column can be converted into Fahrenheit by reading across on the same line to its equivalent in the center column. Similarly, any Fahrenheit temperature in the right column can be expressed in Celsius by reading across on the same line to its equivalent in the center column. (2) The temperature of interest can be found in the center column, and its Fahrenheit equivalent may be found to the right, or its Celsius equivalent to the left.
Temperature conversion formulas: °F = (°C × 9/5) + 32; °C = (°F − 32) × 5/9

6.2.1 Loss of Volatiles

6.2.1.1 Water

The earliest stage of heat application is called the water-smoking period in contemporary studio and commercial ceramic firings. During this stage, the remainder of the mechanically combined or pore water left in the clay after drying at ambient temperatures is removed, along with surface-adsorbed water. The water turns to vapor and is largely driven off by 200°C, accompanied by most of the initial weight reduction and shrinkage in a clay body. If water is removed too fast from fine clays, or if it remains in the clay owing to incomplete drying, hairline cracks may occur. The piece may even explode in firing: when water turns to steam it increases 1600–1700 times in volume.

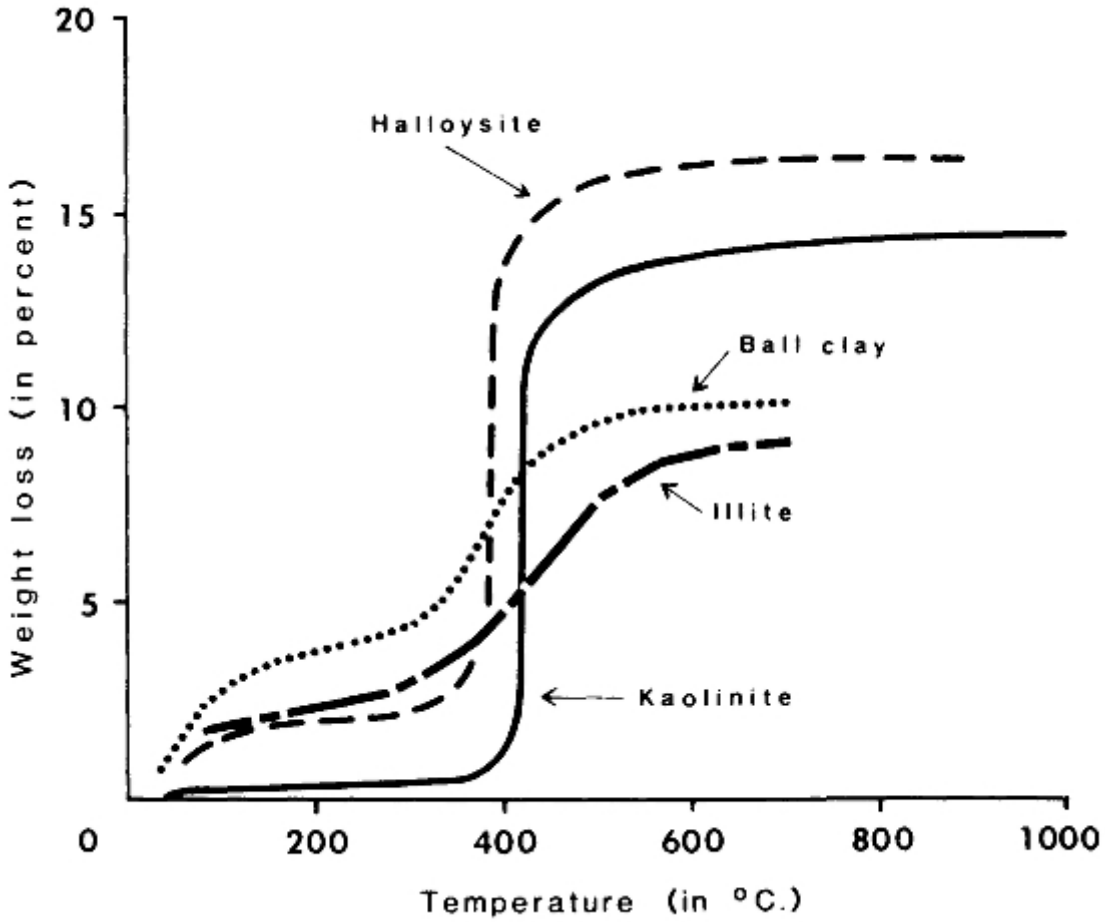

Figure 6.1 Weight loss of four clays with heating. The rapid increase in weight loss at about 400°C corresponds to dehydroxylation. After Norton 1970: fig. 15.4.

Problems linked to water loss are particular hazards in smectite clays. Because of their small particle size and ability to hold water and ions between unit layers, smectites have more surface-adsorbed water to lose initially. On heating, they give up a great deal of water at very low temperatures between 100°C and 200°C, much of it being the interlayer water held between the silicate sheets. This water removal, if graphed by clay weight, often shows a double peak. This may be attributable to the movement of two types of water: water of hydration from adsorbed ions on the surface of the particles, and water adsorbed onto the surface of the clay particles themselves (Grim 1968: 314).

As the temperature rises, the chemically combined water begins to be eliminated. This process is known as dehydroxylation, an endothermic reaction (heat is absorbed) in which the hydroxyls (OH^-) in the chemical composition of the clay minerals, existing as interlayer or lattice water, are removed. The temperatures of dehydroxylation vary with rate of heating and type of clay mineral (fig. 6.1). Kaolinite, for example, loses most of its water rather abruptly between 400°C and 540°C, up to 650°C, although other kaolin minerals such as halloysite behave differently (Frost and Vassallo 1996). Illite clays lose much of their water within a broad range of temperatures, but tests of sample

clays show that dehydroxylation may not be complete even at temperatures of 950°C (e.g., Escalera et al. 2012). The dehydroxylation of smectites occurs over a broad range of temperatures that vary by mineral species and composition, and requires less heat than that for kaolins.

Much of the clay used for non-industrial pottery is not mineralogically pure but consists of several clay minerals mixed together. This mixing seems to lower the temperature at which the hydroxyl water is lost and also makes the loss more gradual, thus smoothing out the dehydration curve (Grim 1968: 349).

6.2.1.2 Organics and Impurities

Organics represent a second component of the clay material that volatilizes and contributes significantly to weight reduction and shrinkage in firing. Present in varying amounts in nearly all clays, organic material begins to oxidize from the surfaces at 200°C or shortly above this temperature as it volatilizes in the form of CO and CO_2 gases. Carbon is eliminated from the interior to the surface of the formed piece as this process continues under elevated temperatures. At temperatures of 300–500°C or higher, the surfaces of the clay piece may have a pronounced black color as carbon moves to the surfaces before being burned off.

How long it takes to burn out the organics, and at what temperature, depends primarily on three factors:

- Conditions of firing: In a fully oxidizing atmosphere, the carbonaceous matter can be readily removed from the clay beginning at low temperatures. In open or mixed-fuel firings, however, the atmosphere is generally highly variable and rarely completely oxidizing because of the proximity of the fuel and the prevalence of combustion products in the air. Even in non-electric kilns, changes in oxidation can be caused by the rhythm of stoking fuel, although these variations are less pronounced than those occurring as part of open firings.
- Fineness of the clay: Fine texture affects the number and size of capillaries allowing carbon to move from the interior to the surfaces. Carbon burns out of fine clays more slowly than coarse clays because of the more restricted pore spaces within which oxidation and movement of particles can occur.
- Clay mineral: Certain kinds of clays, especially the three-layer smectites, tend to bind carbon fairly easily and strongly within their chemical structure and to give it up slowly on heating.

All in all, carbon usually is not effectively eliminated until temperatures above 600°C —usually about 750°C or more—are reached, and the atmosphere must contain free oxygen.

Incomplete oxidation of carbon leads to the dark core often seen in broken cross sections of ceramics fired to relatively low temperatures for short periods and in very fine-textured pottery. In sandy, coarse-textured pottery fired at low temperatures, retained organic matter often helps maintain the integrity of the piece, which would otherwise be weak and crumbly if the organics were completely oxidized. Brief firing might be an adaptation to such clays.

Besides water and organics, other impurities and inclusions also may volatilize in the temperature range of 500–800°C. Among these are carbonates, sulfates, and sulfides. Salts such as NaCl, Na_2CO_3, or $MgSO_4$ may migrate to the surface of the clay piece during drying and decompose on heating, releasing CO_2 and SO_2 and contributing to the weight loss. Chlorides react with any iron present to form $FeCl_3$, which volatilizes readily at about 800°C.

Table 6.2 Firing Shrinkage and Absorption of Some Pottery Clays

	Fired to Cone 04 (1060°C)		Fired to Cone 4 (1186°C)		Fired to Cone 9 (1280°C)	
Clay Type	% Shrinkage	% Absorption	% Shrinkage	% Absorption	% Shrinkage	% Absorption
Ohio red clay	11.5	3.9	12.5	0	Bloated	
Red clay	11.0	9.7	15.0	3.4	15.0	0
Stoneware clay	9.0	12.2	10.5	8.4	12.0	3.2
Stoneware clay	6.5	16.8	8.5	11.6	10.5	5.3
Common surface clay	10.0	1.5	Bloated		Fused	
Saggar clay	10.0	9.5	13.0	16.0	16.0	5.0
English ball clay	14.0	16.0	18.0	15.0	18.0	2.0
Fireclay	8.0	11.7	10.0	8.9	11.0	6.3
Florida kaolin	12.5	25.2	16.5	12.7	18.5	6.5
Georgia kaolin	8.0	29.6	9.0	26.9	12.0	22.9

Source: Rhodes 1973: 313.

6.2.2 Shrinkage

As heating continues, the net effect of the breakdown and removal of chemically combined water, organic matter, carbonates, and salts is continued weight loss and shrinkage of the clay body beyond the initial drying. Both kinds of changes are negligible in a representative kaolin clay up to about 450–500°C but are significant at higher temperatures. Shrinkage occurs largely because the clay particles continue to draw together as these constituents are eliminated from the system. Shrinkage is accompanied by increasing density and decreasing porosity of the clay body as pores close (table 6.2). At higher temperatures, shrinkage increases as new minerals form and the clay body melts into a glassy phase.

As in drying shrinkage, firing shrinkage occurs in linear and volume dimensions. Also, shrinkage frequently is differential, following patterns caused by preferred orientation of the clay particles and exaggerated by the additional shrinkage that occurs during firing. Particle-orientation shrinkage effects can relate to methods of forming: for example, they are pronounced in seams of wares cast in molds. If the oriented particles exist primarily on the surfaces, as from burnishing, then cracking or crazing from shrinkage stresses can be especially severe.

Preferred particle orientation problems may be exaggerated during firing by a thermal gradient—a difference in temperature between the interior and surfaces within the wall of a clay piece. The existence of this gradient can be explained in part by dehydroxylation, which begins and is completed, along with its accompanying shrinkage, more rapidly on the exterior; meanwhile the interior is cooler than the exterior and still expanding (fig. 6.2).

Firing shrinkage and weight loss are measured while heating the clay at a constant rate of temperature increase. Linear thermal expansion may be measured continuously during firing by a recording dilatometer. Weight is measured by a thermogravimetric balance that monitors weight loss on heating (fig. 6.3). Alternatively, the clay pieces may be removed from an electric kiln, carefully weighed and measured while still hot, then returned to the kiln. In such a procedure the humidity of the weighing environment must be carefully controlled, because it can contribute to small weight changes in the fired piece. In most instances, the weight loss and shrinkage are noted as a function of temperature and graphed as such.

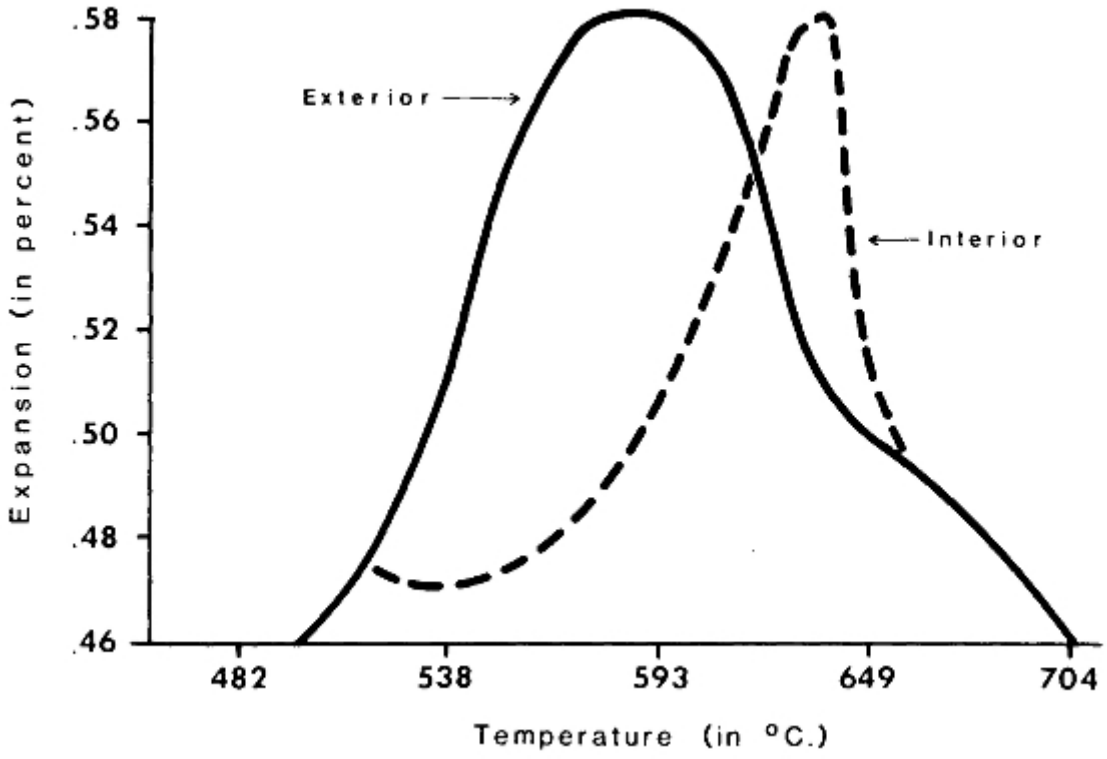

Figure 6.2 Thermal expansion of a whiteware heated in a periodic kiln at temperatures critical for the formation of preheating cracks, comparing expansion of the external surface (*solid line*) with interior core (*broken line*). While the outside expands, cracks form under tensile stresses and progress inward; they remain open as the interior continues to expand and stay open during the remainder of the firing because there are no compressive stresses to close them. Lawrence and West 1982: 146, 148, fig. 9–9.

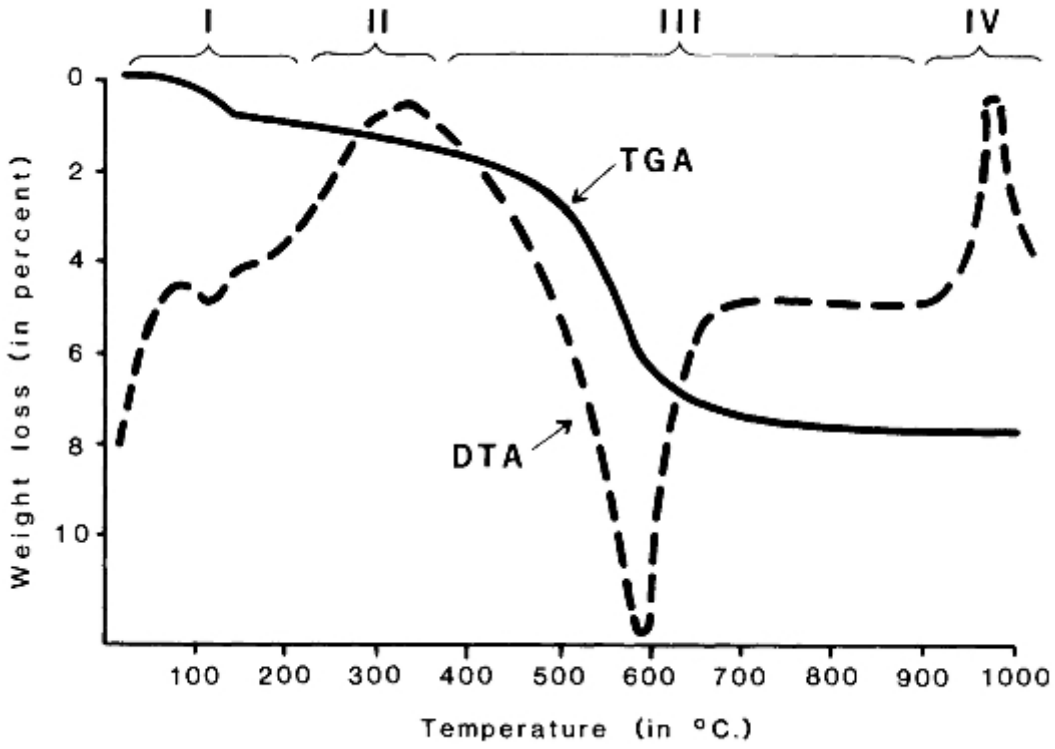

Figure 6.3 Differential thermal analysis (DTA) and thermogravimetric analysis (TGA) of a porcelain insulator body containing approximately 30% clay, heated at 20°C per minute: I—loss of adsorbed water; II—oxidation of organics; III—dehydroxylation, or loss of chemically combined water; IV—crystal formation. After Lawrence and West 1982: fig. 9–5.

6.2.3 Changes in Clay Minerals

At higher temperatures (above approximately 600°C), after the water of hydration is lost from the clay minerals, clays undergo major alterations in their chemical and mineral structures. These changes occur primarily at temperatures rarely, if ever, attained and sustained under the conditions associated with open firing, but some do begin earlier in the firing sequence.

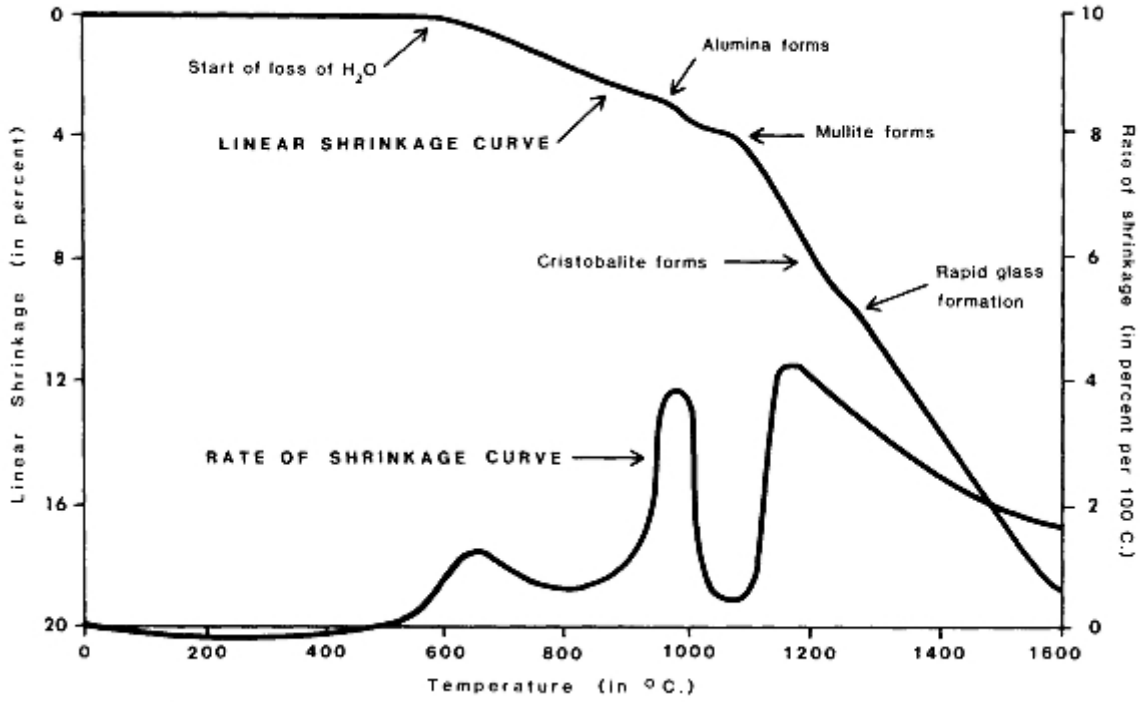

Figure 6.4 Linear firing shrinkage and rate of shrinkage (per 100°C) curves for a kaolin clay. After Norton 1952: 129.

Most studies of thermal changes have been done on kaolin clays (fig. 6.4). When kaolinite is heated above the dehydroxylation range, an altered mineral called metakaolin ($Al_2O_3 \cdot 2SiO_2$) is formed. The disordered crystalline structure of metakaolin retains similarities to that of the original kaolinite and metakaolin can sometimes be rehydrated back to that mineral, even preserving the hexagonal shape of the particles. Metakaolin and other dehydroxylated clays are important in cement industries (Fernandez et al. 2011).

Smectite and illite minerals, which have a three-layer structure, go through the same general transitions, but at different temperatures (higher in illite) and with some variations (fig. 6.5). The lower alumina component and common ionic substitutions in these chemically variable clays have the overall effect of making them less refractory (resistant to melting) than kaolins. Loss of interlayer water may cause irreversible changes at lower temperatures than in kaolinite.

6.2.4 Changes in Inclusions

Quartz's role in a clay body is modified to some extent by the alterations it undergoes on heating. Although quartz is a refractory mineral—it resists melting until 1710°C—during heating to high temperatures it undergoes three transformations in lattice structure and bonding. These changes, which occur at 573°C, 867–870°C, and 1250°C, have accompanying modifications in related properties such as density and specific gravity. For most archaeological pottery, these changes or inversions are of interest in firing; for

studio and commercial pottery, they occur on cooling (they are sometimes distinguished as conversions and inversions; Hamer and Hamer 2012: 325–29).

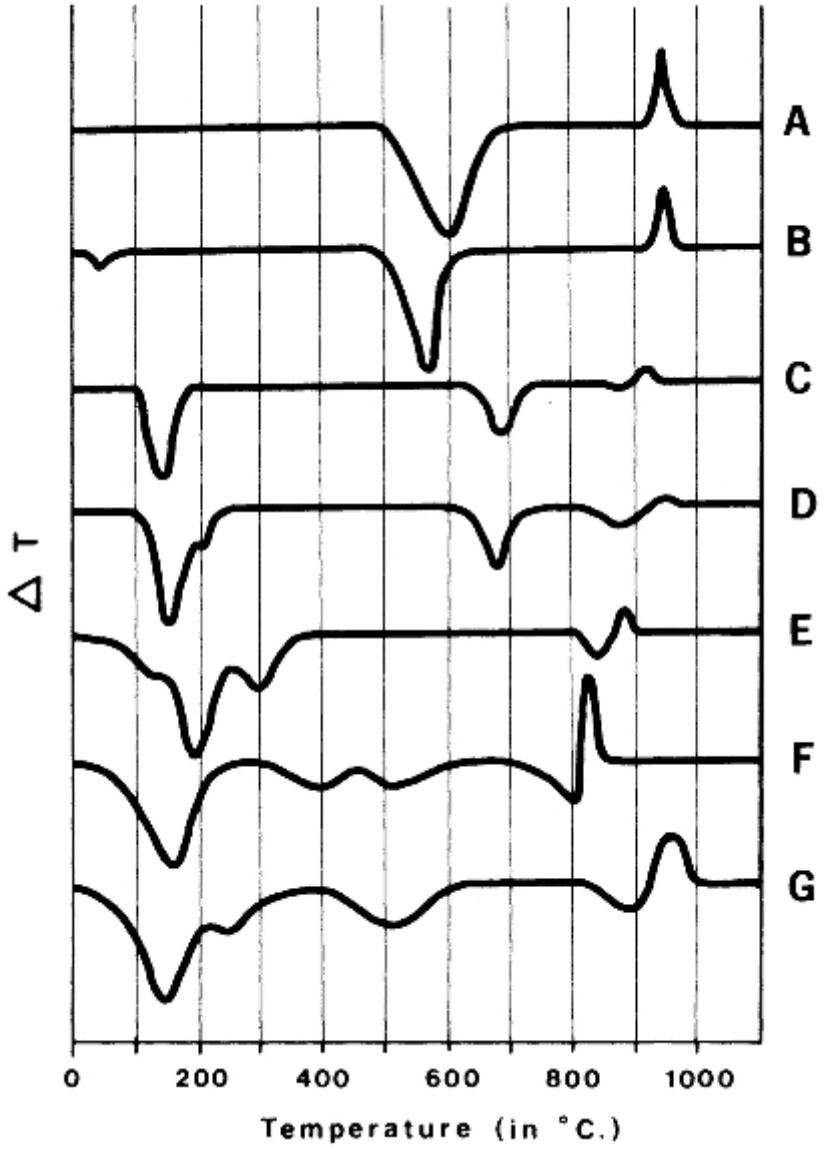

Figure 6.5 Generalized differential thermal analysis (DTA) curves for clay minerals: *a*, kaolinite; *b*, halloysite; *c*, Na-montmorillonite; *d*, Ca-montmorillonite; *e*, vermiculite; *f*, sepiolite; *g*, palygorskite. Note low-temperature (100–200°C) endotherms corresponding to dehydroxylation of clays with quantities of water in their chemical structures (montmorillonite, vermiculite, sepiolite, and palygorskite). After Neumann 1977: fig. 20.

The first inversion, which begins around 550°C and is completed rather rapidly at 573°C ± 5°C, is a change from **α** (alpha) to **β** (beta) quartz (Hamer and Hamer 2012: 328). This structural transformation is accompanied by a volume expansion of the quartz grains of up to 3%. This expansion may not have any effect on the fired clay body, however, because it occurs more or less simultaneously with the removal of large amounts of water when the body is shrinking. In studies of thin sections of archaeological pottery from the New World, Anna Shepard (1976: 29) noted no

shattering of quartz grains attributable to this phenomenon, perhaps in part because of the very rapid heating schedule used by the potters.

The role of quartz in enhancing desirable properties of fired clay bodies or eliminating undesirable ones has been the subject of numerous studies. Quartz reduces firing shrinkage, but unless it is of very small particle size or is present in very small amounts, it may also lessen fired strength. This occurs in part because of the expansion accompanying the **α–β** inversion, but also because of the microcracking resulting from larger particles at high temperatures.

Feldspars, when present in fine particle sizes and subjected to the high temperatures of ceramic firing, do not undergo inversions of their atomic structure like quartz; instead they begin to melt. Feldspars naturally present as residual minerals in primary clays or added by means of crushed rock are rarely fine enough in grain size to bring about the fluxing action in low-temperature firings.

Calcium carbonate—calcite, limestone—has a distinctive property that affects its performance in fired clay bodies: it decomposes on heating. The exact temperature or temperature range at which this occurs is a matter of debate, and it appears to vary with time, atmosphere, particle size, presence of other minerals (e.g., in a clay body), and other factors. Calcium carbonate may begin to decompose at about 700°C and complete the reaction around 900°C. In any case, when it decomposes it forms lime (CaO) and carbon dioxide gas (CO_2):

$$CaCO_3 \xrightarrow{650\text{–}900^\circ C} CaO + CO_2\uparrow$$

The problem for pottery arises when calcareous clays fired to this temperature range are cooled. CaO is hygroscopic—that is, it absorbs atmospheric moisture—and over time it picks up moisture from the air, forming quicklime, $Ca(OH)_2$, and releasing heat. This is accompanied by volume expansion, which sets up stresses in the surrounding clay body, causing cracking and spalling (lime popping). Most noticeable when the lime particles in the clay are comparatively large, the rehydration of the lime lowers the strength of the fired ware and in extreme cases may cause the entire body to crumble (Butterworth 1956; Rye 1976).

Several solutions are possible (Laird and Worcester 1956). If the lime is present only in very fine particles, the rehydration and expansion tend to be less damaging. The presence of salt in the clay may prevent crumbling (Klemptner and Johnson 1986; Rye 1976). A procedure called docking—wetting the newly fired and still hot vessels with water—can also prevent spalling (Klemptner and Johnson 1986). Alternatively, the clay may be fired in a reducing atmosphere, or oxidation-fired either below 700°C or above 1000°C, at which temperatures rehydration does not occur.

6.3 Changes at High Temperatures

Additional changes may take place in a clay body with firing to temperatures of 900–1000°C and above. As with changes at lower temperatures, the degree to which they proceed depends on a combination of time and atmosphere: the duration of the soak or period of holding a constant maximum temperature.

Studio potters are concerned with the work-heat ratio, the effect of a given amount of heat in a given amount of time to bring about the intended characteristics of a mature clay body. In modern electric or gas kilns the rate of heating can be carefully controlled and monitored up to the maximum desired temperature. This control—and measurement of work heat (not simply temperature alone)—is usually achieved with reference to pyrometric cones. Pyrometric cones are small pyramidal indicators compounded of materials similar to glazes, the precise composition varying such that they soften and bend at specific temperatures given a standard rate of temperature increase.

Table 6.3 Pyrometric Cone Equivalent (PCE) Temperatures, Orton and Seger Cones (°C)

	Orton Cones		
Cone Number	Large Cones[a]	Small Cones[b]	Seger Cones
020	635	666	670
019	683	723	690
018	717	752	710
017	747	784	730
016	792	825	750
015	804	843	790
014	838		815
013	852		835
012	884		855
011	894		880
010	894	919	900
09	923	955	920
08	955	983	940
07	984	1008	960
06	999	1023	980
05	1046	1062	1000
04	1060	1098	1020
03	1101	1131	1040
02	1120	1148	1060
01	1137	1178	1080
1	1154–1160	1179	1100
2	1162–1165	1179	1120
3	1168–1170	1196	1140
4	1186–1190	1209	1160
5	1196–1205	1221	1180
6	1222–1230	1255	1200

7	1240–1250	1264	1230
8	1263–1260	1300	1250
9	1280–1285	1317	1280
10	1305	1330	1300
11	1315–1325	1336	1320
12	1326–1337	1335	1350
13	1346–1349		1380
14	1366–1398		1410
15	1431–1430		1430–1435
16	1491		1460
17	1512		1480
18	1522		1500
19	1541		1520
20	1564		1530

Source: After Grimshaw 1971: tables XIIa,b; Nelson 1984: 325.
Note: Orton cones are used in America, Seger cones are used in Europe.

[a] Bending temperatures for large Orton cones are based on a heating rate of 150°C (temperature rise per hour). Nelson and Grimshaw give different temperatures for the cones; where two temperatures are given, the first temperature is from Nelson, the second from Grimshaw.

[b] Bending temperatures for small Orton cones are based on a heating rate of 300°C (temperature rise per hour).

Several kinds and sizes of cones are used, which are numbered from 020 through 01 to 15 (table 6.3) and accommodate temperatures from roughly 635°C to 1430°C. Typically, several cones will be selected to bracket the desired kiln temperature: one that softens or melts at a higher temperature (guard cone), one at a lower temperature (guide cone), and one at the desired maturing point. The three cones are set upright in a pad of clay and placed in the kiln where they are visible to the potter. When the lowest cone deforms and bends into a semicircle, the proper temperature is approaching and adjustments should be made to hold the temperature constant; if the highest cone bends, it indicates overfiring (fig. 6.6).

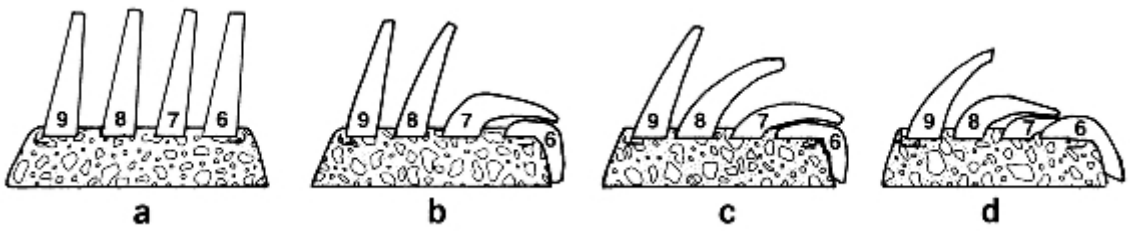

Figure 6.6 Pyrometric cones used in gauging a hypothetical firing: *a*, unfired cones; *b*, overfiring for cone 7, underfiring for cone 8; *c*, proper firing for cone 8; *d*, overfiring for cone 8, but not quite proper firing for cone 9.

The controlled rate of heating and sustained high temperatures permitted by enclosed kiln-firing bring about not only the melting and fusion of glazes but also the maturation of stoneware and porcelain bodies, giving them their characteristic hardness, strength, and impermeability. This maturation involves a complex set of changes in individual mineral constituents, as well as changes in the ceramic body as a whole.

6.3.1 Changes in Mineral Constituents

At temperatures above 900–1000°C, the clay minerals lose all water and their lattice structure collapses irreversibly. If the firing is long enough, these minerals break down and form new silicates called, appropriately, high-temperature minerals. In kaolins, at about 950°C metakaolin decomposes and recrystallizes as spinel plus free silica, accompanied by a sharp increase in shrinkage. Alumina-rich spinel ($MgAl_2O_4$) is the earliest and most common of these high-temperature alteration products. Between 1050°C and 1275°C, spinel forms mullite ($3Al_2O_3 \cdot 2SiO_2$) and more free silica. Mullite exists in needles or rod-like crystals, which reinforce and strengthen the fired piece.

The lattice structure of smectites is generally maintained until approximately 800–900°C, above which these clays may undergo two kinds of reactions. In some smectites, especially those with Al^{3+} ionic substitutions in the tetrahedral layer, spinel begins to form; in others, generally those low in iron, quartz rather than spinel develops. The order and temperature of appearance of higher-temperature minerals such as mullite, cristobalite, and cordierite also vary in these two types of smectites. The presence of lithium, sodium, and potassium reduces the development of high-temperature minerals and also lowers the maximum temperatures to which they persist.

The structure of illite clays persists until 900°C or beyond, sometimes being identified at temperatures as high as 1000°C. Spinel forms at about 900–1000°C and mullite, too, may appear at this relatively low temperature.

In quartz, a second inversion begins at 870°C and, after lengthy firing, results in a change from **β** quartz to disordered cristobalite. “Pure” cristobalite slowly forms at 1470°C. Between these two temperatures tridymite may form. These are very slow reactions (requiring days of firing; Hamer and Hamer 2012: 326) and involve major rearrangements of the strongly bonded silica-oxygen tetrahedra. Much of the cristobalite in fired clay bodies probably comes not from the quartz changes but from the free SiO_2 liberated when mullite forms. Most non-kiln firings are far too brief to even approach the tridymite and cristobalite inversions.

Nonetheless, the presence of fluxes can hasten the quartz inversions and also cause the quartz particles to dissolve to form a siliceous glass, with a volume increase of

2.05%. The viscous silica undergoes very little thermal expansion with increasing temperatures, but the incompletely dissolved crystals have a large thermal expansion coefficient. On cooling, differential shrinkage causes stresses that may result in the cracking of large crystals (~30 μm), creating microcracks in the clay body. Particles of 8 μm or less melt easily to form a glass. As the body cools, **β**-cristobalite reverts to a lower temperature form, called **α**-cristobalite, at a temperature between 200°C and 270°C, accompanied by a volume contraction of approximately 2%. There is no reversion back to **α**-quartz.

When subjected to high-temperature firings, feldspars continue to melt, instead of undergoing changes in their atomic structure. Finely ground (to 40 μm, or 0.04 mm) feldspars are used in the ceramic industry as fluxes (see Schramm and Hall 1936) because of three properties. First, most feldspars have a relatively low melting point or high fusibility: Na-feldspars begin to melt at 1118°C and K-feldspars at 1150°C. Ca-feldspars or plagioclases, high in alumina (36.7%) and low in SiO_2, melt at a much higher temperature, 1550°C, but that temperature can be lowered if other feldspars are present or if limestone is added. Second, feldspars are highly viscous on melting and form a thick, rather than thin and runny, liquid. Third, their very fine particles enhance their readiness to sinter and fuse. The net result is a dense ceramic body with reduced porosity (table 6.4).

Any calcite present in a clay does not rehydrate on cooling after being fired above 1000°C, because at these temperatures the calcium in most clays becomes a part of the liquid phase with sintering and vitrification. New high-temperature calcium compounds are formed, such as calcium silicates (wollastonite, $CaSiO_3$) or calcium ferrosilicates, depending on the composition of the body. Melting of calcium compounds is accelerated in a reducing atmosphere and when the lime is in extremely fine particles (Maniatis et al. 1983; Tite and Maniatis 1975b).

Table 6.4 Fluxing Action of Different Particle Sizes of Feldspar and Effects on Porosity of a China Clay

Feldspar		Porosity					
			Firing Temperature (°C)				
Size (mesh)	Amount(%)	Unfired	1000	1100	1180	1280	1350
40	40	31.0	34.5	30.95	23.65	10.95	4.96
	20	36.6	40.0	37.15	30.0	18.45	14.21
100	40	32.85	36.5	30.8	17.1	6.6	1.4
	20	37.0	41.0	38.4	27.5	14.4	8.87
200	40	35.1	38.6	22.65	14.8	6.0	. . .
	20	38.05	41.55	33.6	23.7	10.5	7.11

Source: After Grimshaw 1971: table XII-XVI.

6.3.2 Sintering and Vitrification

The complex co-occurring changes in the components of a ceramic at high temperatures —breakdown and formation of new minerals—produce significant changes in the body as a whole. The most important of these are sintering and vitrification:

- In ceramic sintering (Rahaman 2003), the surfaces of particles begin to stick to or fuse with other particle surfaces at a temperature about half that of the material's melting point. Sintering may occur as a solid-state or liquid-phase reaction:
  - In solid-state sintering, the surface diffusion of atoms between the particles forms a join or "neck" between them, and no melting or liquid phase is involved. Various complex processes account for the transfer of material between adjacent grains (Anseau et al. 1981; Burke 1985; Kingery et al. 1976: 469–79), which usually results in shrinkage of the mass, in pores' changing shape (becoming more spherical) or elimination, and in densification.
  - In liquid-phase sintering the fusion takes place when some constituents of the body (e.g., fluxes such as feldspars) begin to melt, forming a liquid. As sintering proceeds more of the solid melts and incorporates additional particles. The grains draw closer together and the pores between them get smaller, giving rise to shrinkage, loss of porosity, and densification. This shrinkage is enhanced by the surface tension forces of the glassy melt between the particles.
- In vitrification, a glassy phase forms as a result of continued heating and extension of liquid-phase sintering. In this process, defined as densification with the aid of a viscous liquid phase (Kingery et al. 1976: 490), the crystalline particles melt and form a dense, glassy phase, pores are eliminated, and the mass shrinks considerably. If vitrification proceeds to an extreme, the entire mass loses its form and may warp or slump under its own weight.

The rate of sintering is more or less inversely proportional to particle size, occurring with powdered materials in ceramic industry. In addition, sintering and vitrification

begin earlier in materials with fine particle sizes, whether clay or feldspar, than in coarse ones, even below the standard vitrification temperatures of the constituent minerals. This is an important point, not just in terms of high-temperature bodies and glazes of commercial or studio ceramics, but also for understanding the advantages of using fine colloidal clays for slips. Many common and naturally occurring materials or impurities in clays can act as fluxes in the body or in slips if they have extremely small particles. For example, finely divided iron in a reduced state (ferrous oxide, FeO) may act as a flux at low temperatures between 800°C and 900°C (see Grimshaw 1971: 275–97). Similar action may be caused by mica (see Arayaphong et al. 1984), boron, or lead minerals.

Box 6.1 The Thermal Reaction Sequence

Each clay mineral behaves in a unique way during firing, and the many kinds of clay bodies also behave distinctively, depending upon their particular constituents and their particle sizes. This variability also is a consequence of the conditions of time, temperature, and atmosphere during firing. Despite these differences, it is possible to create a general outline of the reactions and changes that take place, with varying degrees of completion, in a clay body during heating up to about 1400°C (table 6.5).

- Room temperature to 200°C: As heating begins, the last of the mechanically combined water (pore water, adsorbed water) is eliminated, disappearing as water vapor (water smoking). In three-layer clays, such as smectites, a considerable degree of interlayer water may be lost as well. Little shrinkage occurs.
- 200–400°C: Organic matter begins to oxidize, migrating from the interior to the exterior of the clay walls, blackening the surfaces, before being driven off as CO_2.
- 450–600°C: Dehydroxylation or loss of chemically combined lattice water begins in all clays, accompanied by shrinkage. In kaolins the loss is relatively quick and complete, but it is more gradual in illites and smectites.
- 573 ± 5°C: Quartz converts from the α, or low-temperature form, to the β, or high-temperature form, with a slight volume expansion.
- 750–850°C: Most organic material has been burned out of the clay. With the removal of lattice water, kaolin and smectite minerals begin to lose their crystalline structure. Calcium carbonate dissociates, changing to CaO and giving off CO_2 gas.
- 870°C: β quartz begins slowly altering to cristobalite.
- 800–900°C: Sintering may begin in bodies or coatings with extremely fine particle sizes, especially of iron.
- 950°C: The structure of most kaolins and smectites is irreversibly lost, although that of illites may persist. With the loss of structure, the formation of high-temperature alteration products of the clay minerals, such as spinel, begins, along with pronounced shrinkage.
- 1050–1200°C: Spinel changes to needlelike crystals of mullite. Feldspars begin to melt, dissolving both the silica formed at the same time as the spinel and the quartz already present in the body. This initiates the glassy (vitrified) phase of the ceramic: pores begin to close, porosity rapidly diminishes, and shrinkage accelerates.
- Above 1200–1275°C: Porosity may increase as gases form in the melting body, and if there is no way for them to escape these gases can cause bloating. Tridymite begins a slow change to cristobalite. Sillimanite, kyanite, and cordierite, all metamorphic minerals, form as high-temperature phases of the clay minerals, accompanied by a sharp increase in shrinkage.

Table 6.5 Changes with Firing and Cooling Temperatures

Temperature (°C)	Change in Clay or Kiln
100–200	Clay begins to lose adsorbed water (water-smoking period)
200–225	Alpha-beta inversion of cristobalite (on cooling after firing)
470	Lowest temperature at which a red glow can be seen in the dark
450–550	Kaolinite loses hydroxyls; metakaolin forms
500	Organic matter oxidized
550–625	Dull red glow, visible in daylight
550–650	Montmorillonite loses hydroxyls
573	Alpha-beta inversion of quartz
600–800	Micas lose hydroxyls
800	$FeCl_3$ volatilizes
870	$CaCO_3$ dissociates to CaO plus H_2O at or by this temperature; tridymite forms from beta quartz
886	Lead melts
950	Spinel forms; CaO reacts with clay forming calcium silicates (wollastonite); bright red heat
960	Recrystallization of metakaolin begins (on cooling)
1000	Formation of calcium ferrosilicates; calcareous clays turn pale yellow or olive
1050	Light-yellow or orange heat in kiln
1100	Mullite forms
1118	Na-feldspar (albite) begins to melt
1100–1200	Vitrification range of ball clays
1150	K-feldspar begins to melt; white heat in kiln
1200	Gypsum dissociates; lead volatilizes
1250–1290	Biscuit firing range for bone china; cristobalite forms from tridymite
1320–1450	Maturing range for hard porcelains
1470	Cristobalite stabilizes
1550	Ca-feldspar (plagioclase) begins to melt

~1700	SiO_2 melts
~2000	Al_2O_3 melts

Source: After Cardew 1969: app. 14.

7 Glazes

> As a teacher, I have always talked about the similarity of the process of glaze making and firing to that of food preparation and cooking. . . . This analogy . . . is closer than most people think. Both involve a transformation process which is a chemical reaction of various minerals under different levels of heat. [A chart] shows a list of the various minerals found in eggs, butter, sugar, flour, and milk. All these minerals can be commonly found in ceramic glazes.
>
> Hopper 2009: 56

The complex composition and firing of ceramic glazes represent a special instance of firing to vitrification. A ceramic glaze is a particular kind of glass, a highly viscous, noncrystalline coating melted and fused with the surface of a ceramic at high temperature. Glazes are cooled rapidly (supercooled) and solidify without reforming a crystalline structure, thus retaining some of the characteristics of a liquid. Glaze manufacture is dependent both on knowledge of how to prepare a substance that will melt to form a glass and on the ability to sustain a high enough temperature in firing so this melting can take place.

The composition of a glaze requires complex formulas and calculations of quantities of ingredients, along with considerable experimentation and practical testing to achieve the desired outcomes. For millennia such calculations and testing had to be done through practice, with outcomes subject to the vagaries of firing conditions. The multitude of glaze recipes (table 7.1) in the literature today demonstrates that the creation of successful glazes for art and industrial ceramics required a sophisticated understanding of chemistry, and shows how the sensitivity of glaze ingredients to changes in firing temperature and atmosphere can be manipulated to create different textures and colors. Calculations are now vastly simplified by computer programs and the outcomes are more secure because of highly temperature-controlled kilns.

Glazes may be described and classified in many ways—for example, by their composition, by how they are made, by the wares on which they may be used, and by how they are fired and their maturing temperatures (Hopper 2009; Rhodes and Hopper 2000).

Table 7.1 Glaze Recipes

1. Low-fire (cone 06) lead glaze, resistant to food acids
   36.78 white lead
   18.95 soda feldspar
   9.78 gerstley borate
   4.90 boric acid
   6.80 kaolin
   21.70 silica
   0.83 zirconium oxide
2. Wood ash glaze, fired at cones 8–10
   39.0 wood ash (mixed)
   29.5 kona F4 feldspar
   10.0 whiting
   19.5 kaolin
   2.0 bentonite
3. Mat glaze, fired at cones 10–12
   40.0 potash feldspar
   22.3 whiting
   21.0 kaolin
   16.7 silica
   4.4 titanium oxide
4. Celadon glaze, fired at cones 8–10
   79.5 potash feldspar
   6.2 whiting
   14.3 flint
   2.0 red iron oxide

Source: Nelson 1984: 330.
Note: Amounts given by weight (percentage).

7.1 Components and Kinds of Glazes

Glazes (and glasses) have three major components, which have been described as network formers, network modifiers, and intermediates (see Rhodes 1973: 88–94, 104–11). Types of glazes are distinguished by their composition, chiefly with reference to the principal modifier. Ideally present in extremely tiny particle sizes (200 mesh sieve), each ingredient is important to the character of the final material:

- Network formers: Formers create the largely unordered structure of the glass by combining oxygen atoms with certain cations into oxides, and by the arrangement of the resultant tetrahedra. The primary network or glass former in ceramic glazes is silica, SiO_2 (see fig. 2.4), although boron (B_2O_3) and phosphorus (P_2O_5) can meet these structural criteria.
- Network modifiers: Modifiers are oxides, usually metallic oxides, which enter holes in the network of silica tetrahedra. These oxides usually have larger ionic radii than silica and weaken the bonds in the network. In so doing, they play the key role of lowering silica's high melting point, and thus commonly act as fluxes. Important modifiers include Na_2O, K_2O, PbO, CaO, and MgO. The potassium and sodium used in alkaline glazes have high coefficients of expansion, resulting in poor fit to the ceramic body, but the problem of crazing can be ameliorated with the addition of lead (Rhodes and Hopper 2000: 130, 136, 203–4).
- Intermediates are oxides that replace part of the silica and usually serve one or both of two "tempering" functions. One function is to increase the viscosity (stiffness) of the glaze, which is lowered by the fluxes. Because a glaze is melted in place on a body, it must exhibit just the right degree of fluidity, not too much or too little. A second function of intermediates is to strengthen the glaze in firing—for example, to reduce crazing. Al_2O_3, ZnO, ZrO_2, and CdO are common intermediates. Small amounts of alumina (often added as ball clay) provide the requisite stiffness and also prevent the reformation of crystals during cooling, although too much will cause a glaze to appear matte and "dry" rather than shiny (Rhodes and Hopper 2000: 135, 136).

In addition, organic materials may be added as binders to increase the strength of the raw glaze (Nelson 1984: 263). These additives, such as gums or sugars, toughen glazes for overpainting (e.g., in majolicas) and protect them against accidental damage during drying, stacking in storage, or handling while setting the kiln.

Categorized by method of manufacture, glazes may be either compounded or noncompounded. Compounded glazes may be made either from a variety of raw ingredients or from frits. Glazes made of raw materials are less expensive and more resistant to chemical and mechanical attack. Frits are basically premelted glazes: raw materials (e.g., silica and a flux) are melted together, cooled, and ground into a powder before being combined into a glaze mixture (see Rhodes and Hopper 2000: 213–15). Fritted glazes can be fired at lower temperatures and have fewer flaws than glazes compounded of raw materials, but they are more costly. Whatever the method of compounding, the ingredients are mixed as liquids and applied by dipping, pouring, splashing, painting, and spraying.

The lead glaze is a major glaze category for earthenwares, ancient and modern (see Rhodes and Hopper 2000: 197, 204–6). With a low melting point of 886°C, lead may

be applied as a noncompounded glaze by simply brushing the surface of a vessel with powdered lead oxide (called litharge) or galena (lead sulfide; PbS). In compounded glazes, lead acts as a flux, lowering the melting or fusion point of the glaze mixture and allowing it to form a glass at lower temperatures. Lead glazes are generally clear, glossy, and often green although yellows and reds are also common; copper was a typical colorant. Lead glazes have the additional advantages of being easy to fit to the clay and firing with few flaws. Lead volatilizes at about 1200°C and for that reason is not used for high-fired glazes.

Majolica is a fine earthenware covered with a white (or light-colored) enamel: a soft or low-firing glass applied to pottery or metal. This enamel is a lead glaze made opaque by adding stannic (tin) oxide, typically as the mineral cassiterite (SnO_2). The tin has low solubility in the glaze solution and remains as tiny unmelted particles in the cooled glaze, resulting in its opacity (Mason and Tite 1997; Molera et al. 2001: 334; Vendrell et al. 2000). Opaque glazes mask defects in finish or color of the vessel body and provide a clean background for painted decoration, typically in blue or multiple colors. Majolica and similar tin-enameled wares were made throughout the Mediterranean region and spread to the Americas with Spanish and Portuguese conquest and colonization.

Generically, majolica enamels are low-fired alkali glazes with either sodium or potassium as fluxes. Potassium was frequently obtained from wine lees in Italy, whereas in Muslim areas such as southern Spain, where alcohol was proscribed, soda ash from burned marsh grasses was used. The clay body was typically calcareous, which meant that it had a high coefficient of expansion, as well as a light color after firing. Many of the fabrics of colonial Latin American tin-enameled wares lacked this calcium and were red and iron-rich. The soak period of tin-enameled wares in early Europe and the colonial Americas are unknown, but generally low-temperature glaze firings may need to be 6 to 12 hours in length (Hopper 2009: 53).

Noncompounded glazes are simple to produce. An ash glaze, for example, makes use of the ashes of fired material, such as wood, grasses, leaves, or other vegetal material, to contribute potassium or soda as fluxes. Such a glaze may be created by dusting the vessel surfaces with ash—this may also occur by the circulation of ash in the atmosphere of a wood-fired kiln—or by adding ash as components of the glaze (see Hopper 2009: 119–22; Leach 1976: 159–63). An example is the *khār*, or sintered plant ash, manufactured by Pakistani potters as a glaze constituent (Rye and Evans 1976: 180–85). The earliest glazes manufactured in various parts of the world have been of this alkaline ash type, which required no special knowledge or compounding.

Another type of noncompounded glaze is a salt glaze, a once-fired alkali glaze created by throwing or shoveling salt (NaCl) into the kiln at temperatures of 1100–1250°C. The salt decomposes, with sodium acting as a flux when the ions make contact with the ingredients of the surfaces of the vessels, while the chlorine volatizes and escapes as a gas (Starkey 1977: 2):

$$2NaCl + H_2O \xrightarrow{(heat)} 2HCl \uparrow + Na_2O;$$
$$Na_2O + Al_2O_3 \bullet 4SiO_2 = Na_2O \bullet Al_2O_3 \bullet 4SiO_2.$$
(soda) (pot surface) (salt glaze)

The result is a thin, mottled glaze with a pebbly texture often likened to orange peel.

Many of these common ceramic glazes can be dangerous because of toxic ingredients (Brody 1979: 84–85; Nelson 1984: 210–23). Some problems affect the potters: ash glazes, for example, are caustic and should not be stirred with the hands. Similarly, it has been known since the nineteenth century that lead glazes can be toxic both in application and in use (see Rhodes and Hopper 2000: 21). The toxicity of the raw glaze compound is reduced by using purchased frits, but this does not significantly reduce the risk of lead poisoning if acidic substances (orange juice, wine, etc.) are stored or served in low-fired lead-glazed ceramics. Different threats are posed by the chlorine gas released in salt glazing: those stoking the kiln should wear masks and the area should be well ventilated. In addition, the chlorine also threatens the environment, having contributed to acid rain and deforestation in Westerwald, Germany, where famous salt-glazed stoneware is produced (Lowenstein 1986: 394).

7.2 Colorants

Besides the three major components of glazes, these coatings also include colorants that participate in a complex series of high-temperature chemical processes. Coloring agents in glazes are primarily oxides of the so-called transition-metal elements—titanium, vanadium, chromium, manganese, iron, cobalt, nickel, and copper (Hopper 2009: 171–75; Rhodes and Hopper 2000: 219–25). These elements generally have two incompletely filled electron shells in their atomic structures, and their coloring ability is linked to the absorption of part of the radiant energy of light by electrons that jump between shells. The color can also be traced to the presence of the ion in multiple valence states, such as iron in the ferrous-ferric state, which is dark brown or black. Finally, some ions that produce characteristic colors, such as copper, chromium, and manganese, are called chromophores.

The transition elements have ionic radii intermediate between sodium and silica, and so they may be either formers or modifiers of the glaze structure. Depending on their role—which is in turn related to the composition of the glaze and the presence of other oxides as modifiers and intermediaries as well as on the firing temperature and atmosphere—individual elements can give rise to very different colors (table 7.2). In general, a broader range of colors can be attained at lower temperatures (e.g., below 1125°C), because at higher temperatures many of the elements are unstable and volatilize.

Colorants are added to glaze preparations in several ways. One way is with finely ground oxides (from carbonates or salts) of the transition metals; carbonates seem to be most typically employed because they naturally occur in fine particle sizes. Another way is through commercially prepared stains; common today, these are often combinations of oxides purchased from color companies (see Hopper 2009: 193–208). Strong colorants such as cobalt may be added in amounts as low as a fraction of a percent, while as much as 5–6% or even 10% of other weaker materials may be added (see Rhodes and Hopper 2000: 219–25). Glazed wares may also be colored by specially prepared underglaze pigments, which are very finely ground and contain little flux in their composition. They are, as the name implies, painted on a vessel before the glaze is applied, and because they do not flow as the glaze melts, they allow for fine detail in decoration (see Brody 1979: 89–92; Rhodes and Hopper 2000: 260–62).

Table 7.2 Color Development from Adding Colorants to Glazes

Colorant	Oxidizing Atmosphere	Reducing Atmosphere
Iron	Tan, yellow, brown; green with copper	Gray, blue, green (celadon), red
Copper	Green; blue-green (with cobalt or alkaline formula)	Red to reddish purple
Cobalt	Blue	Blue
Manganese	Purple, purplish blue, black	Brown
Tin	Opaque white	Volatilizes
Nickel	Gray or brown	Gray or gray-brown
Chromium	Green	Yellow; turquoise with cobalt

Source: After Rye 1981: 47; Rhodes 1973: 317–18.
Note: Any of these colors will vary depending on the presence of other colorants in the glaze (see Rhodes 1973: 218), as well as the overall composition of the glaze (lead versus alkaline, for example) and firing temperature.

Iron is often added as hematite or ferric oxide (Fe_2O_3). Depending upon the composition of the glaze and firing characteristics, it can yield colors from cream through brown to black and even green. In lead glazes, for instance, iron yields warm tones of tan, yellowish brown, amber, and reddish brown, whereas in alkaline glazes iron is responsible for cooler tones in the same range. In a lead glaze with tin oxide present, the iron creates mottled cream colors. If large amounts of iron are present (7% or more), the glaze colors will be dark brown or black. In a reducing atmosphere (and with the presence of barium) an iron-bearing composition results in the cool grayish-green glaze colors of celadon (Vandiver and Kingery 1984), the jadelike stoneware that dates from the Song dynasty (early second millennium AD) in China and was widely copied in Japan and Korea.

Copper is a versatile glaze colorant, readily available from copper salts or the carbonate minerals malachite and azurite. It needs to be added in amounts of 2–5% to create the desired color. Copper glazes were probably the earliest to be used in antiquity, both in the Near East and in China. In a reducing atmosphere the color is a deep red or reddish-brown (often called oxblood, or *sang-de-boeuf*); copper is probably the best source of a high-fired red color, which is difficult to create. Oxidizing conditions give copper a blue or green color. In high-alkaline (Na or K) glazes copper is a distinctive turquoise, and the presence of barium and boron will also give rise to bluish or greenish tones. Added to lead glazes, copper usually results in a green color, but because it boosts the release of lead it is not an appropriate glaze for tableware. Copper itself is volatile above approximately 1225°C.

Cobalt, used by the Persians in the ninth century and by the Chinese in their famous blue underglaze porcelains in the fourteenth century AD, is the most stable of the pigments. Its colors vary little with changes in temperature and atmosphere of firing or with composition of the glaze. Cobalt is also an extremely strong colorant, with amounts as little as 0.25% giving rise to a definite blue color. Manganese with cobalt will contribute a purplish tone, and iron, chromium, or copper will give bluish-greens. Cobalt forms variable and blotchy colors above approximately 1250°C.

Manganese, available as manganese dioxide or pyrolusite, is usually added in amounts of 2–6%. It is a weak colorant, yielding a plum or bluish-purple in alkaline glazes and a softer purple in lead glazes; in the presence of iron it is black. At temperatures above about 1200°C or in reduction, manganese yields brown.

Chromium yields a highly variable range of colors, including red, yellow, pink, brown, and green, depending on the composition of the glaze and the firing temperature. In low-lead glazes lacking zinc it yields a green color; with zinc it is brown. In low-fired lead glazes with low aluminum, chromium will give an orange or red color, whereas at higher temperatures it is brown or green; the presence of sodium gives rise to yellow, and adding tin makes the glaze pink or maroon. Usually added in amounts ranging between 0.5% and 5%, chromium is volatile above approximately 1190°C.

Several additional elements may be colorants in glazes. Titanium (in rutile or ilmenite) gives rise to brown, or it may instead be added for textural interest (mottled, speckled, opaque, or crystalline glazes). Nickel is used for green or brown. Uranium, although largely unavailable since World War II with the development of the nuclear weapons industry, was earlier used for yellow, red, or coral colors. Some elements are typically added by commercially prepared stains: these include cadmium and selenium for reds, vanadium and antimony for yellow, and gold for pink, red, or purple. These ingredients may be undesirable for a variety of reasons: cadmium and selenium are toxic on tableware; antimony is unstable above approximately 1135°C; and gold (and also platinum) is prohibitively expensive.

7.3 Firing

Glazes may be applied to an unfired clay object and the piece finished in a single firing, but typically two firings are used, and sometimes three. The first firing of the unglazed body is called the bisque or biscuit firing and is commonly carried out at temperatures of 900–1000°C. The ware is then cooled, the glaze is applied, and the glazed pieces are refired in the glost firing. The bisque firing makes the piece stronger (than green ware) for dipping in the glaze and decorating, permits it to undergo most or all of its firing shrinkage, and leaves the body porous enough that the glaze adheres better. The glost firing may be done at about the same temperature as the bisque firing, or it may be higher or lower. Chinese glazed porcelains, for example, often had lower-fired lead glazes applied to the high-fired biscuit porcelain body (Medley 1976: 14). Some wares, such as Medieval Spanish luster wares with overglaze decoration painted with oxides of silver or gold, were fired three times (Van de Put 1911).

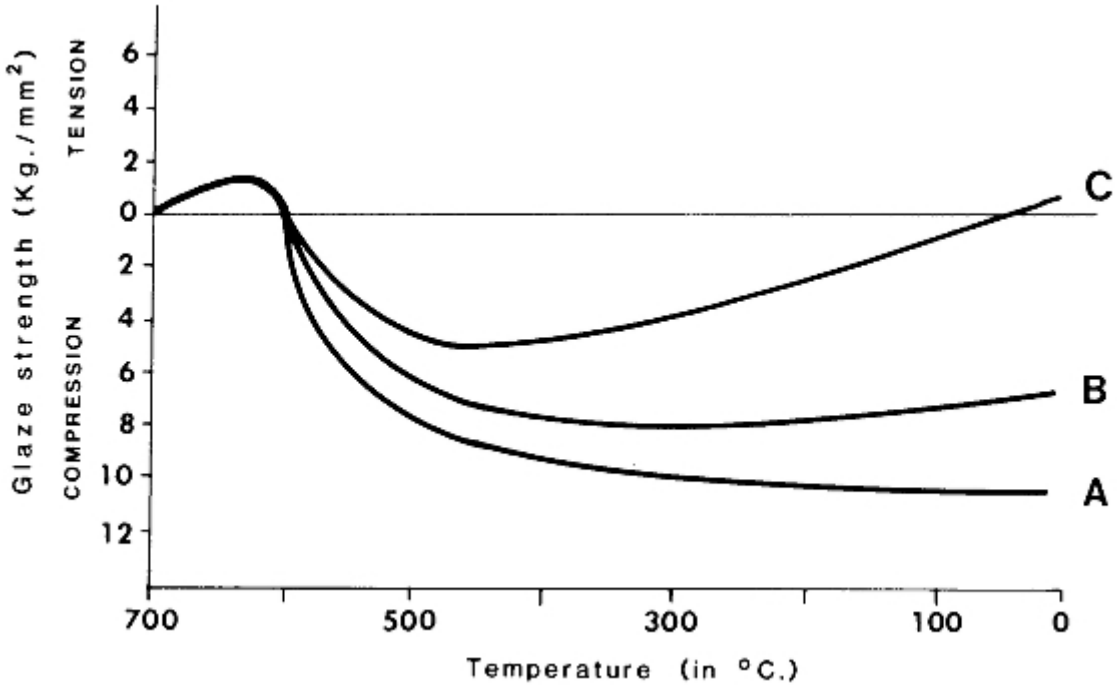

Figure 7.1 Stresses induced in glazes during cooling: *a*, the body has a significantly greater coefficient of expansion than the glaze, putting the glaze in high compression, which may cause it to peel; *b*, the body has a slightly higher coefficient of expansion than the glaze, reducing the stresses but leaving it in slight compression; *c*, the body and glaze are of comparable expansion, placing the glaze under tensile stress in cooling, which may lead to crazing. After Grimshaw 1971: fig. XII.6.

Glazes may be classified as high-temperature (or hard) and low-temperature (or soft), depending on whether the glost firing is below 1150–1200°C or above 1200–1250°C. The maturing temperature of a glaze is generally a function of the amount of

silica relative to the amount of fluxes (Rhodes 1973: 164). High-fire glazes typically contain feldspars and/or alkaline earth minerals such as calcium carbonate (whiting), dolomite, or barium carbonate. Low-fire glazes (see Brody 1979: 75–89) either are alkaline in composition (containing borax or soda ash, for example) or are lead glazes, with lead as the principal flux. Although low-temperature glazes can be used on high-fired (bisque) bodies, it is difficult or impossible to use a high-temperature glaze on a body with a low maturing temperature (such as an earthenware) because of the danger of overfiring and deformation (see Rhodes and Hopper 2000: 135). Glaze compositions generally have a firing temperature tolerance of about 30°C (Rhodes 1973: 124).

Defects in fired glazes can be caused by improper compounding, careless application, and over- or underfiring (for general discussions of glaze flaws, see Hamer and Hamer 2012; Hopper 2009: 128–34; Lawrence and West 1982: 189–91; Rhodes and Hopper 2000: 254–59). During firing, the glaze and clay surface actively react with each other, especially at high temperatures, with the glaze fusing to the body. A critical concern in glazing is "fit"—the dimensional adjustment of a glaze to a clay body—which is related to the thermal expansion and shrinkage rates on cooling of the two materials (fig. 7.1; for discussion of physical, mechanical, and thermal stresses impacting glazes, see secs. 18.1.2, 19.2, and 19.3). In general, if a glaze contracts very slightly more than the body after cooling, it compresses the body and so strengthens it.

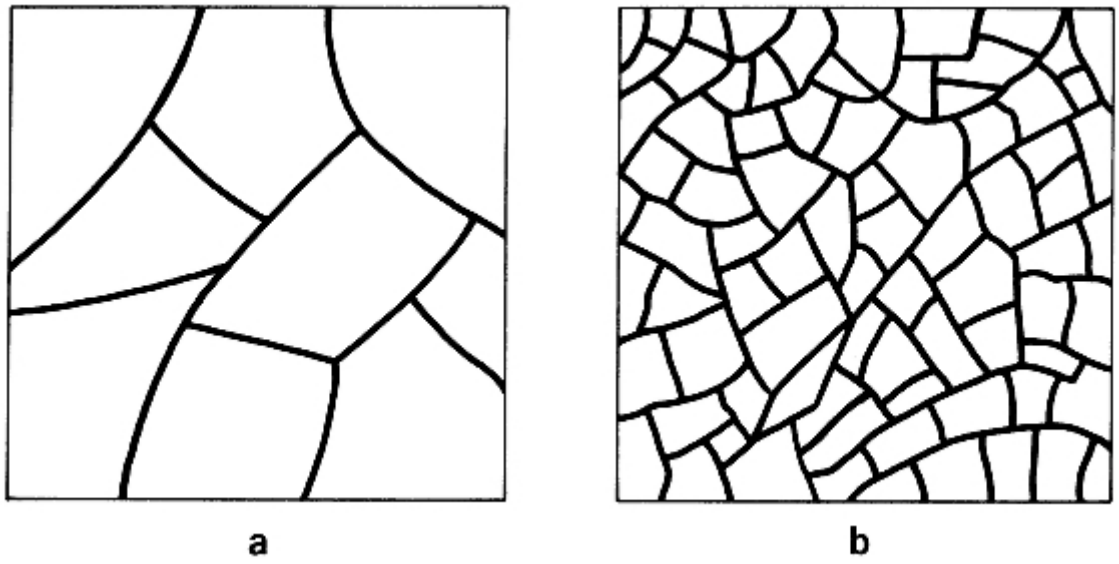

Figure 7.2 Crazing of a glaze under tensile stress: *a*, low stress; *b*, high stress. After Lawrence and West 1982: fig. 11–4.

Unequal contraction rates, however, can cause a variety of defects which are typically only visible in the end product:

- Crazing occurs when the glaze contracts more than the body and develops a network of surface cracks (fig.7.2).
- Shivering occurs when the glaze contracts less, or more slowly, and separates from the body.

· Crawling is a flaw related to surface tension, in which the glaze contracts to expose the body, often in attractive (but unintended) ways.

Firing at the wrong temperature may bring about other defects such as improper development of color and gloss. Firing at too high a temperature, for example, may cause the glaze to volatilize or run off the pot. Glazes fired too rapidly or overfired may develop bubbles, blisters, or pinholes; underfired glazes are generally rough to the touch and dull or matte in appearance. An unintended matte surface also may be caused by too much alumina or CaO.

Part 3

Behavior: Ethnographic Perspectives on Pottery Making

> Clearly things made people, and people who are made by those things go on to make other things. The central question, however, is not whether this does or doesn't happen, but in what kind of way it happens.
>
> Pinney 2005: 256

Pottery manufacture, like other productive technologies, represents a point of direct interaction between people and their environment. One popular theoretical approach to material culture in anthropology and archaeology focuses on technologies and the producer's choices and decisions in fabrication (e.g., Gosselain 1994; Lemonnier 1993). Another influential approach goes beyond, viewing objects as having life cycles or cultural biographies (Gosden and Marshall 1999; Kopytoff 1986; Shott 1996), from formation through use to discard. To understand pottery and its life cycle, Part 2 began with the raw resources and their chemical, geological, and materials engineering-related properties. Part 3 moves to the human behavior involved in using these resources and their properties: potters' decisions about acquiring and manipulating them to form, finish, dry, and fire a strong, attractive vessel that will be acquired ("adopted") for use by a consumer and have a long and successful use-life (Part 4).

Because many things can go wrong as a pot is being shaped, dried, and fired, a complex of beliefs, taboos, and rituals may surround potters and potting. For example, the act of obtaining clay, particularly special kinds of clay, is often the focus of taboos or rituals. In Papua New Guinea, among the Azera only married women who had not yet had children could gather clay, and then only at certain times (May and Tuckson 1982: 136). They must wear traditional dress and cannot smoke, chew betel, or speak pidgin.

Among the Sepik River Kwoma, on the other hand, clay is gathered only by fully initiated men and their wives (May and Tuckson 1982: 218–20). Pots may be made only by married women who have borne two or three children or by men who have reached the third stage of initiation. Washing, loud conversation, wood chopping, sago cutting, and digging yams and taro are all forbidden during Kwoma pottery making; menstruating and pregnant women may not go near the clay, and neither sex may engage in intercourse. Similarly, female potters in the Chorotegan area of Costa Rica did not make pots during menstruation or for three months after giving birth (Stone 1950: 272).

Outsiders were commonly forbidden to watch as pottery was being made, as among the Azera (May and Tuckson 1982: 136). Pamunkey potters in Virginia did not like to have the process observed because they believed that if someone looked too hard at a pot in the making it would break (Stern 1951: 19). Similarly, in Chinautla, Guatemala, passersby do not look at pottery during its firing because of the widespread belief that the "evil eye" will cause an unsuccessful firing and make pottery turn black (Reina 1966: 272).

Rituals may be especially important if the pottery itself has ritual uses. Among the Huichol of Mexico, for example, the water mixed with clay for a double-mouthed ceremonial vessel should come from the sacred caves where these vessels are frequently placed (Weigand 1969: 14). Huichol mothers also sometimes smeared blood from the heart of a hummingbird on a young girl's wrist to enhance her skill at pottery making or at artisanship in general (Weigand 1969: 31).

Varied signs may be sought to predict rainfall or success in firing during the rainy season. Potters in Chinautla look at the position of the moon or the behavior of vultures: if vultures "make a blowing noise while flying by, it is a sign that there will be rain, which prevents the firing of the pottery: but if they whistle, the weather will be favorable for firing" (Reina 1966: 92).

8 Manufacture

> A pot in order to be good should be a genuine expression of life. It implies sincerity on the part of the potter and truth in the conception and execution of the work.
>
> Leach 1976: 20

Although ceramic objects have served as utensils in day-to-day activities for millennia, the number of communities in which pottery water jars and cooking pots are made and used in traditional ways has drastically diminished. Cheap and durable containers of metal and plastic are readily available as substitutes, and potting is being abandoned. Fortunately, a multitude of reports have documented the manufacture and use of ceramics around the world before the activity disappeared. Information often can be found in published and unpublished accounts by explorers, military and religious personnel, and colonial administrators in non-Western and traditional societies dating back to the mid-nineteenth century and sometimes considerably earlier (e.g., Brongniart 1844; Bushell 1910; Picolpasso 1934; Staehelin 1965). Their usefulness varies, as some are little more than commentaries on an intriguing bit of artisanship or notations on household goods. In the late twentieth century, however, research programs in ethnoarchaeology and experimental archaeology began to be directed toward systematic investigation of the relations among technology, economy, and materiality as part of the broader social fabric.

A summary of the full range of practices involved in all steps of pottery manufacture known from the ethnographic present is not possible here (for Africa, see Gosselain 2010), and to contextualize non-industrial pottery making there is no substitute for perusing these accounts. Nonetheless, a sampling of the variability in these procedures will help the reader envision similar behavior in antiquity.

8.1 Obtaining and Preparing Resources

The most important resource in pottery manufacture is clay for the vessel body. Other resources include materials for temper; colored clays and minerals for slips, paints, and glazes; and fuel for firing. These resources may be obtained in diverse ways (Arthur 2006: 31–35; Fontana et al. 1962: 55; Graham 1922: 15; LeFree 1975: 7, 10; Neupert 2000; Nicholson and Patterson 1985b: 224–25; Thompson 1958: 66; Weigand 1969: 35).

Clay sources are sometimes open to all and widely shared, or individual landowners, potters, workshops, families, or communities may have the rights to mine or sell clay (e.g., Arnold 2000: 349–351; Arthur 2006: 31–34; Neupert 2000). At Bailén, Spain, for example, potting factories own specific deposits, and these are inherited through families along with the business (Curtis 1962: 491). Or, potters may exploit secret locations that are not divulged to outsiders or competitors. Potters may use clay from a single source or employ different sources interchangeably. The clay may be mined by the individual potter (or a relative or coworker) as needed for each batch of pottery; several families may work cooperatively so it becomes a social occasion; or mining may be carried out by landowners or other individuals with no family ties to the potters. In general, substantial reserves of clay are not kept on hand except in large potting industries (e.g., Balfet 1965: 164), as it is often difficult to store clay in quantity and protect it from rain or contamination. In hot, dry areas of Pakistan, potters may briefly store prepared clay-temper mixtures in cool underground pits, which are advantageous under variable weather conditions or during especially hot times of the year (Rye and Evans 1976: 40, 45).

8.1.1 Distance

Potters travel variable distances to obtain their resources. Surveys of the ethnographic literature have quantified the areas within which potters acquire their clays, tempers, slips, and pigments, calling attention to interesting patterns (Arnold 1980: 149, 1985: 39–49). In the 110 cases for which there are data on clay gathering, the distance from potting location to clay source varied from less than 1 km to 50 km. Of 31 cases detailing temper procurement, the range was from less than 1 km to 24 km. Approximately 85% of the tabulated materials are procured within 7 km (4.35 mi) of the potters' living or working areas, and this range seems to be the area or catchment for primary resources. The distance most frequently traveled for both clays and tempers is less than 1 km from the settlement (table 8.1), which Dean Arnold (1980: 149) labeled the "preferred territory of exploitation."

It is difficult to interpret these distance data, however, because no clear causal relationship can be reliably inferred between resource location and potting location. Do potters establish themselves within a 7 km radius of desirable resources? Or

conversely, does a given settlement of potters choose to exploit only clays within a 7 km radius to achieve least cost? Can the location of suitable clays be used to predict the location of potters, or is the existence of potting communities a reliable predictor of the presence of suitable clays within 7 km? Clearly, for predictive purposes these relations are easily oversimplified, and many other factors are involved: scale of production, bulk and value of the goods produced, location of the market for the products, and the presence of suitable fuel. Another consideration for archaeologists is the transportation technology available for moving these bulky, fragile materials.

Table 8.1 Distances between Potters and Their Clay, Temper, and Slip and Paint Resources

Distance (km)	Clay Source[a]	Temper Source[b]	Slip and Paint Sources[c]
<1	25	14	. . .
1–2	35	5	. . .
2–3	12	1	4[d]
3–5	11	6	6
5–10	15	4	3
10–15	3	. . .	4
15–25	7	1	2
25–50	2	. . .	6
>50	. . .	. . .	11
Total N cases	110	31	36

[a] From Arnold 1985: table 2.1. Some rounding of numbers and grouping error has resulted in minor distortions of the raw data.

[b] From Arnold 1985: table 2.2.

[c] From Arnold 1985: table 2.3.

[d] Three cases are given as distances ranging up to 2.5 km.

The collocations of resources and workshops may be most directly related at the extremes of manufacturing scale or intensity (Nicklin 1979: 442–43; van der Leeuw 1977: 70–71). Potters in a large-scale industry may act on least-cost principles and establish manufacturing centers close to their resources to save time and labor in procurement and processing as well as to ensure a large supply of clays of known quality and performance. Clay may literally be obtained from the potter's own backyard: this is true of the utility pottery industry of Bailén (Curtis 1962: 491) and is especially common in the traditional manufacture of heavy clay products such as bricks and roof tiles (fig. 8.1). Similarly, ceramic shipping containers, such as the amphorae of the ancient Mediterranean world and "olive jars" or *botijas* of the imperial Spanish trade, are typically manufactured close to port cities or locations of commodity production, near Seville in the latter case. Itinerant jar makers of Thrapsano, Crete, located their workshops in fields where the three essential materials for pottery making —clay, fuel, and water—could be easily acquired (Voyatzoglou 1974: 18).

At the opposite end of the production scale, where pottery making is sporadic, undertaken when an accident necessitates replacing a water jar or cooking pot, potters also may be inclined to use whatever clay is handy rather than making a considerable effort to secure clays from a greater distance. Fulani potters in Bé, North Cameroon, for example, obtain clay from a pit only fifteen minutes' walk from the village (David and Hennig 1972: 5). The Diola of southern Senegal manufacture pottery during the two or three months following their harvest season and procure clay slightly more than 1.5 km away (Linares de Sapir 1969: 3).

Figure 8.1 A brickyard in highland Guatemala. The plastic clay soils of the valley are excavated and mixed with water, then shaped in rectangular wooden molds to form bricks, which can be seen drying under cover in the foreground and to the right. In the background are the kiln and adjacent storage area.

At intermediate scales of production the distance potters travel to obtain clays varies considerably. Potters in Pakistan use clay near their workshops; if it is not suitable for particular uses, they prefer to modify its characteristics rather than to acquire better clay from farther away (Rye and Evans 1976: 126–27). Gamo potters in Ethiopia primarily acquire their clay from sources within the predicted 7 km (Arthur 2006: 31), but potters in parts of Nigeria traveled as much as 10 or 15 miles for clay (Nicklin 1979: 441, 445). In Melanesia the Amphlett Island potters' clay is brought twice a year from Fergusson Island, the returning canoes laden with a ton or more of the special clay used for large, lightweight jars (Lauer 1970: 166; Malinowski 1922: 283–84). Shipibo-Conibo (Peru) potters obtain clays and other resources by canoe over distances of 365 km, but within this range, 84% of the potters' procurement decisions conform to least-effort expectations of travel distance (DeBoer 1984: 542–46).

Distances for obtaining slip and paint resources ranged up to 800 km (Arnold 1985: table 2.3). These materials are often acquired by trade rather than mined by the potters; because they are used in significantly smaller quantities than are clays and tempers, least-cost principles are less likely to be determinative. At Santa Clara Pueblo, New Mexico, for example, although potters gather clay from pits between 3 and 4.5 miles from the pueblo, the white kaolin for their painting is secured from an undivulged source 100 miles distant (LeFree 1975: 7, 22; for discussion of white pigment, see also Plog 2003: 687–88). Similarly, the aromatic slip clay used by potters in Tonalá, Mexico, comes from 100 miles away (Díaz 1966: 141). Rare cobalt for the blue decoration on Chinese porcelains and New World tin-enameled wares was initially imported from sources thousands of miles away (Rice 2013b).

8.1.2 Modification

Clays can sometimes be used in their natural state as dug from the ground, without modification. Kalinga potters of northern Luzon in the Philippines, for example, use a sandy clay that requires neither additional temper nor sifting or cleaning (Longacre 1981: 54). More typically, however, clay has to be processed to make it suitable for use. Potters' clay preparation activities vary irregularly along a continuum from very simple to highly intensive, according to the time and effort devoted to cleaning the clay and modifying its properties.

Inclusions often must be removed from relatively coarse surface clays, which may simply entail picking foreign matter—rootlets, leaves, pebbles, and so forth—out of the clay by hand. Such cleaning is common with clays that are relatively coarse, stiff, and lean in their handling characteristics, and those with quantities of organic matter or large fragments of minerals that can damage products under certain firing conditions (e.g., calcite or mica). The cleaning process may be considerably more complex, however, and involve drying the clay, then crushing, grinding, and winnowing or sieving it. The latter may be accomplished with baskets, or sieves may be constructed of palm ribs, rawhide punched with holes, perforated sheet metal, screens, or cloth. Levigation (mixing the clay with water and allowing the coarser particles to settle out of the suspension) is usually done in relatively large, mass production industries. One enormous levigation tank used in the production of Arretine ware had a capacity of ten thousand gallons (see Peacock 1982: 54, 122). At lesser scales of production, it is more common to find smaller containers for simply soaking and stirring clays and then evaporating, decanting, or screening them to eliminate impurities.

Other clays, especially those that are extremely fine-textured and sticky, must have modifiers added to make them usable for pottery making. These added substances are commonly and generically referred to as temper (chapter 4).

After the clay or clay-temper material has been made plastic by adding water, the mass is usually systematically manipulated or wedged by kneading with the hands,

cutting and recombining, repeatedly slamming onto a hard surface, or foot-treading (fig. 8.2). This arduous activity assures a uniform, homogeneous distribution of moisture and inclusions, and improved workability, by eliminating air pockets, locating and eliminating lumps (of clay or foreign matter), and mixing wetter and drier portions to ensure that all clay particles are wet. Although potters typically wedge their clay after it has been combined with temper and made plastic with water, the potters of Chinautla first wet their clay then wedge it by kneading it with temper: about 10% by weight of very fine pumice (Reina and Hill 1978: 32–33). Adding temper to wet rather than dry clay may allow finer control of texture and plasticity.

Figure 8.2 Foot trampling clay in Nabuel, Tunisia. Photographed by Robert H. Johnston, reprinted from *Pots and potters: current approaches in ceramic archaeology*, ed. P. M. Rice (Monograph 24, Institute of Archaeology, University of California, Los Angeles, 1985).

Foot-trampling or treading is more common in preparing extremely large batches of clay. In this process the clay is spread on a clean floor or in a pit and systematically trod, often by a young apprentice in the workshop. In modern factory operations, a pug mill or deairing pug mill (operating with the clay in a vacuum) accomplishes these tasks.

Today's artisan and industrial potters know that aging or souring a wet clay mass can improve its workability: aging allows the water to fully permeate the mass and wet the surfaces of each clay particle, thereby increasing plasticity. This process may be augmented by bacterial action or by adding small amounts of acidic substances. There is

little mention of systematic aging in the ethnographic literature, however. Potters of San Luis Jilotepeque, in highland Guatemala, mix their finely ground clay with water and let it sit for five or six hours before working with it further (Reina and Hill 1978: 165); the Seri of Mexico rest their clay and dung mix overnight (Bowen and Moser 1968: 92–95). Papago potters of southern Arizona, on the other hand, sometimes store their clay over the winter (Fontana et al. 1962: 57) and potters in Chamula, Mexico, may age clay as long as a year; pots made of unaged clay are regarded as inferior (Howry 1976: 79).

An elaborate system of preparing clays was used in the manufacture of Chinese porcelains. According to an eighteenth-century description written by a master potter (Staehelin 1965: 22–26), the kaolin clay of Qimen, sixty miles northeast of the workshops of Jingdezhen, was washed, crushed, and then rewashed several times. After cleaning it was strained through a sieve constructed of horsehair, then through a bag made of two thicknesses of silk. This purified clay was then formed into slabs that were air-dried before shipment and storage. It was apparently common for the clay workers in Qimen to adulterate the kaolin, however, so it was further washed and purified once it reached Jingdezhen.

8.2 Forming: Techniques and Tools

Many techniques of constructing pots are known, the most common being coiling, pinching and/or drawing, slab modeling, molding, casting, and throwing. These can be variously classified according to whether they are based on a single lump of clay or on successive additions, whether they are entirely manual or if tools are employed (Fewkes 1940, 1941), whether they are primary or secondary (Rye 1981: 62), and whether rotational (centrifugal) force is employed. Another distinction is between hand-built vessels versus those thrown on a wheel.

Several techniques may be combined in making a single vessel—what might be termed compound or composite forming methods. For example, Gamo potters use coiling, drawing, and paddle and anvil (Arthur 2006: 35–42). Compound manufacturing techniques are widespread, which makes it difficult to maintain a clear distinction between so-called primary and secondary procedures. In addition, successive production steps often obliterate evidence of earlier treatments. Thus, unless one has observed the actual forming, it can be a problem to specify the construction procedures, even from whole vessels, although radiography has proven useful for this purpose (see Balfet et al. 1983: 57–67; Berg 2008; Pierret et al. 1996; Rye 1981: 59–81; Vandiver and Tumosa 1995).

8.2.1 Hand Building and Molding

8.2.1.1 Hand Building

Coiling is a widespread manufacturing technique whereby ropes, rolls, or fillets of clay are built up to establish the vessel circumference and gradually increase the height (Blandino 1984). The coils are formed by squeezing or rolling the clay into ropes or fillets with diameters usually two to three times the intended thickness of the vessel. Coiling has three variants:

- Ring-building: individual rings of clay are laid in separate courses atop one another.
- Segmental or composite coiling: a variant of ring-building, each annular course is composed of several segments rather than a single rope of clay extending around the entire circumference of the pot (fig. 8.3).
- Spiral coiling: building with long ropes of clay, each forming more than a single annular course.

Figure 8.3 Potter in Margaurites, Crete, adding a large coil segment at the top of a flowerpot. The join of the coil segments is just visible to the potter's left. The pot is formed on a pivoted turntable, turned by an assistant. Photograph by Lynnette Hesser.

These coiling methods may be used either to form a whole pot or to build parts of vessels, such as the mouth, that are started or completed by other techniques. Successive coils are applied to the exposed upper edge of the vessel wall, often overlapping slightly on the interior or exterior, and pinched to make a firm join. The oblique juncture formed by an overlap allows a stronger bond between the coils because the area for bonding is greater and more direct pressure can be applied than with a vertically placed coil. Continued squeezing, pinching, and drawing of each coil extends the wall above the original height (or diameter) of the coil itself (fig. 8.4). The junctions of the coils are usually obliterated by later finishing treatments, although on some late prehistoric pottery of the American Southwest the narrow coiled fillets were left as originally

applied and pinched, forming distinctive “corrugated” ware (Hegmon et al. 2000; Pierce 2005; Young and Stone 1990).

Coiling can be easily identified as the technique used if the coils were not well bonded. If, for example, the clay dries excessively before the next coil is applied, the join will not be strong, and the stresses of drying, firing, and use may further weaken these bonds. Hairline cracks and distinctive patterns of breakage may be evident along parallel planes, either horizontal or gently spiraling. The fractures themselves are usually relatively smooth and rounded (fig. 8.5), marking the upper edge of a coil that had another applied above it. Coiling is particularly well suited to building extremely large vessels, such as storage jars.

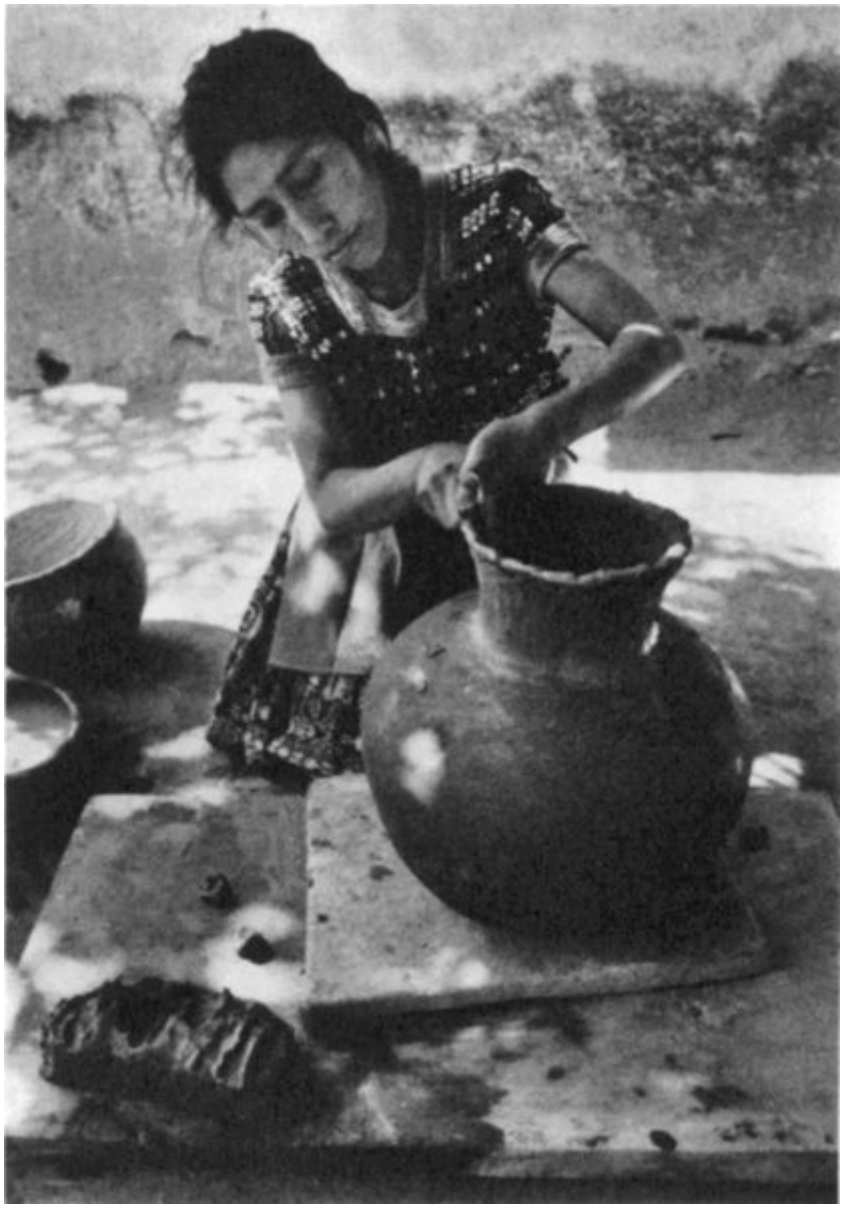

Figure 8.4 Potter in Chinautla, Guatemala, drawing up and smoothing a neck coil on a *tinaja*, or water jar. The body was partially dried before the neck was added. The vessel is formed on a board that permits turning the piece during manufacture.

Pinching and drawing techniques are similar in that a lump of clay is manipulated into a vessel shape without adding more clay. Pinching consists of "opening" the lump by inserting the thumb or fingers or both, then squeezing the clay between the thumb and fingers or between the fingers of both hands. Repeating this action around and over the entire lump thins and shapes it into the desired form. Pinching is often used for small, simple vessels that can be held in the hand or to form the bases of larger vessels that are built up by other methods.

Drawing is similar to pinching but is typically used on larger vessels and emphasizes vertical movement. A large lump of clay is placed on a support and opened by thrusting the thumbs, fingers, or fist into the center. The potter then simultaneously squeezes and pinches with an upward pulling or stretching movement to raise and thin the walls of the emerging vessel; a tool may be used to scrape the clay upward. Both pinching and drawing may be incorporated in an essentially equivalent technique sometimes called lump modeling.

In slab building (also called segmental modeling), a vessel is constructed from one or more slabs of clay that are rolled or patted flat and then joined into the desired shape (Vandiver 1987). In modern studio pottery this technique is mainly used to create rectangular shapes, but it may also be used for cylinders or for building extremely large vessels. "Morsel building" (Fewkes 1940: 172; Roosevelt 1995; Stern 1951: 12–13), in which small lumps of clay are flattened and shaped then successively joined to build the vessel walls upward and around, is a variant of this method.

Figure 8.5 Coil fracture on a sherd of a vessel built by spiral coiling. Note the smooth edges where it was imperfectly bonded with another coil. Maximum exterior diameter, 13.2 cm.

8.2.1.2 Molding

In molding or pressing, a section of clay, often preformed into a disk, is pressed firmly into or over a prepared mold. Molds may be convex, with the clay applied on the exterior, or concave, with the clay fitted to the interior (fig. 8.6); they may form all (full molds) or part of the vessel body (most typically the base; see Reina and Hill 1978: 22); and they may be single units or made in two pieces (Foster 1948b). Two-piece molds, in turn, may be used to form either the upper and lower halves of the vessel or to form two sides of a vessel, joined vertically. Such molds are used today in Ticul, Yucatán, because they permit rapid manufacture by persons with little skill, including children (D. Arnold 1999). Molds may be formed of plaster or fired clay, although ad hoc forms are often created from large broken vessel fragments (as in fig. 8.6), baskets, or depressions in the ground.

To help the newly formed vessel separate from the mold, parting agents—powdered clay, ash, manure, pumice, or fine sand—are used to prevent the clay from sticking. Concave molds are generally easier to use, because during drying the clay will shrink

and detach. With convex molds the potter must be careful to remove the form before the clay shrinks too much (which will cause the piece to crack) but after the clay is firm enough not to slump of its own weight. The use of molds is most clearly evidenced by the marks of seams on the finished vessel, which mark the junctures or edges of the molded pieces. The technique may also be distinguished by a thin surface layer of parting agent or a contrast in textures between very smooth (mold side) and rough (scraped or beaten side) surfaces of the vessel.

Figure 8.6 A woman belonging to a potter caste in Udaipur, Rajasthan, India, making griddles by paddling clay over the base of a water storage jar. The griddles are then dried in the top parts of jars that were damaged in firing or broken after primary use. Women in India do not use the wheel, and these griddles are virtually the only forms they make. Photograph by Carol Kramer.

Molds, especially concave molds, may be incised or carved with some sort of decoration, so that when the clay is firmly pressed into them the molded surface acquires the decoration in relief. This technique was used for much Samian ware (fig. 1.6; Johns 1977a) and is typically associated with rapid manufacture of highly standardized vessels (Peacock 1982: 121, citing Goudineau 1968).

A variant of molding is casting (or slip casting), but it is not known to what extent this technique might have been used, if at all, in antiquity. In slip casting a thin suspension of fine clay in water is carefully poured into absorbent molds (usually of plaster); it is allowed to stand for a short time while some of the clay settles and water

is absorbed into the plaster, then the excess slip is poured off and the piece dries in the mold. The potential for defects in cast ware is high, and many factors must be tightly controlled, especially the viscosity of the slip and the rate of filling the molds (Brody 1979: 27–39; Norton 1970: 101–29).

8.2.2 Supports and Rotational Devices

During forming operations the soft, wet, plastic clay of the growing vessel must be supported in some way, or it will slump. Small objects formed by pinching can be held in the hand, but larger vessels are usually placed on some surface that will accommodate their weight, their shape, and the particular requirements of the forming technique. These supporting devices may be called pot rests or bats (or batts) and may be as simple as a mat, a board (e.g., fig. 8.4), or a clay disk. Vessels with round or pointed bases may be formed on pot rests that help shape the base, such as a mold, large potsherds, or baskets, or supported by rings of cloth, grasses, or other material. Supports placed around the exterior of a pot during drying will help prevent warping (Matson 1974: 346).

In addition, a potter must direct attention to all sides of the vessel during manufacture, either by walking around it or, far more commonly, kneeling or sitting immobile and turning the pot during the work. Although it seems inefficient to keep the vessel fixed and have the potter move around it, this procedure, called the "orbiting" technique, is not unknown (Arthur 2006: 35–42; Scheans 1977: 16–19). The clay is placed on the ground or on some other surface and is shaped by drawing, as at Santa Apolonia (Reina and Hill 1978: 56–63; also Arrott 1953; Lothrop 1927), although coiling is also used. The potter, bent over, moves slowly backward or sideways around the vessel while working.

It is far more typical, however, that the clay is turned while the potter remains stationary. The vessel can be moved by various devices that employ the principles of rotary motion, pivoting, and centrifugal force. The simplest of these devices are supports or turntables that permit rotary motion but are not pivoted and do not supply centrifugal force. For example, large sherds may act as concave basal molds and turn easily because of their curvature. Pottery saucers—round or oval—are used in Peru (Cárdenas 1994; Tschopik 1950).

Small, pivoted turntables (fig. 8.7*a*,*b*) can be rapidly rotated for short periods. They may be turned with the hands or with the feet (Matson 1974: 345; Nicklin 1981b: 184) and may produce the same spiraling grooves seen on wheel-thrown pottery. Many examples of these simple rotating supports are found in the Southwestern United States and Mesoamerica: the Pueblos' *puki* (Guthe 1925: 27–51), the Coyotepec *molde* (Foster 1959), the Acatlán *parador* (Lackey 1981: 65), and the Yucatán *kabal* (Brainerd 1958; Mercer 1897; Thompson 1958: 76–81, 140–41). This last, mistakenly termed a "primitive" potter's wheel, is a small disk or cylinder of wood usually turned by the

potter's feet, thus leaving both hands free for forming and shaping. A smooth, even spin of such devices can be attained only with large, heavy vessels to maintain momentum (Foster 1959: 59).

Rotation, plus the advantage of a pivot to center the revolutions, is also provided by a variety of turntable devices often referred to as tournettes (fig. 8.7*a*,*b*). The tournette typically consists of two stones with a pivot and socket, or a wooden board turning on a stick or pin that acts as a pivot. In form and some aspects of use the tournette mimics the true potter's wheel and it is often mislabeled a "slow wheel." However, this term obscures the very real differences in operating principles between the two. The tournette's small size and weight and its lack of a flywheel mean that it does not rotate with the sustained momentum and centrifugal force of the true wheel. Thus rotary force is not a fundamental part of vessel forming on a tournette as it is with a true wheel.

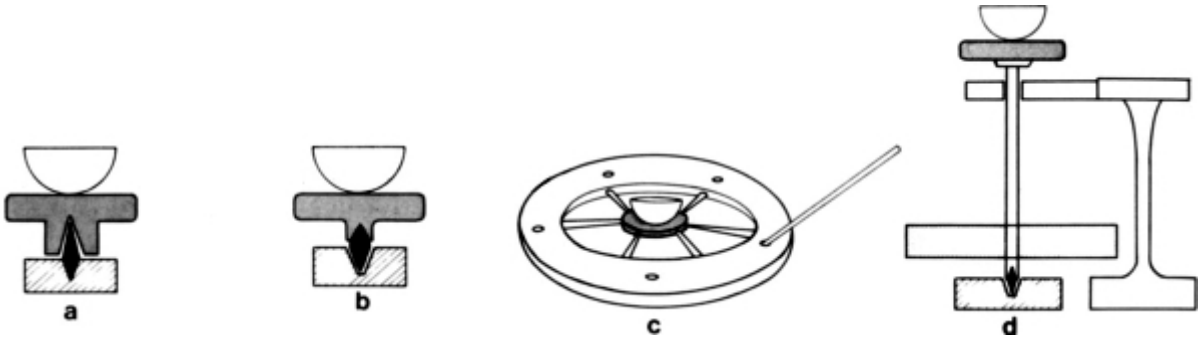

Figure 8.7 Potter's turning devices and wheels: *a*, tournette or hand wheel, high mounted; *b*, tournette or hand wheel, low mounted; *c*, stick (rod, or simple) wheel, turned by propelling a stick inserted in the holes on the outer wheel; *d*, kick wheel (potter's seat is to the right). Heavy stipple indicates wheel head; light stipple indicates flywheel; black lozenge indicates bearing or pivot. After Lobert 1984: fig. 1.

All the devices used to rotate vessels—pot rests, *kabal,* and tournette, and of course the wheel—may be employed at any stage or throughout the entire process of manufacture, from construction, through finishing, to decoration.

8.2.3 The Potter's Wheel

The potter's wheel combines the principle of the pivot with the principles of rotary motion and centrifugal force to create continuous high-speed rotation, allowing the clay to be "thrown" to form a vessel. Critical factors in the use of the wheel for potting are the speed of the wheel, its momentum, and its steadiness or lack of oscillation. Momentum is important because the rotation is slowed by friction from the potter's hands on the clay. Two major types of potter's wheel are known: the kick wheel and the stick wheel (Johnston 1977; Lobert 1984).

The kick wheel, also known as a compound or double wheel (fig. 8.7*d*), consists of two wheels, upper and lower, joined by a vertical axle and mounted with separate bearings in such a way as to prevent oscillation. The potter sits at the level of the

relatively small upper wheel or wheel head, upon which he or she works the clay while kicking the lower flywheel into motion. The flywheel is large and sometimes very heavy (as much as 150 pounds); the large size allows it to store energy supplied by kicking, release it as rotational motion, and maintain the rotational momentum without the upper wheel being slowed by friction. The speed of rotation for shaping certain parts of the vessel is controlled by the rate at which the potter kicks the wheel (see Rye 1981: 74). Modern potter's wheels typically are electrically powered rather than kicked, but the principles are essentially the same.

Figure 8.8 A Muslim potter in Jhanwar, Rajasthan, India, turning a traditional stick wheel, interrupting the shaping of a large vessel used to make milk products such as yogurt. The walls are thrown on the wheel, then the base is paddled in from the bottom of the walls. Photograph by Carol Kramer.

The stick wheel (fig. 8.7*c*) or simple wheel has a large head and a short axle. There is no flywheel; the head itself has sufficient weight to maintain the momentum. Made of

stone, clay, or concrete, the wheel is made to rotate by inserting a stick into a hole in the top and turning it thirty or forty revolutions. This is enough to cause the apparatus to spin on its own for as much as five minutes without stopping. The stick-turning may be done by the potter (fig. 8.8) or by an assistant; the potter sits beside the wheel and throws the pot from the centered lump of clay once the wheel is spinning. It is difficult to maintain continuous rotation with the stick wheel because it is impossible to turn it with the stick while the potter is working (though the wheel may also be hand turned). The stick wheel is commonly used in India.

Compared with the stick wheel, the advantage of the kick wheel is the constant rotation and the lack of interruption while an assistant (or the potter) sets the wheel revolving again. Because the kick wheel is a heavy and rather complex mechanism, unlike the portable stick wheel, it is usually permanent equipment and is typically associated with large-scale workshop production. The apparatus may be raised to the level of a workbench or sunk into a pit.

The clay body prepared for throwing is generally softer and wetter than that used for hand building, partly because the lifting or drawing action used to raise the walls will not allow for a stiff, dry clay, but also because the air circulation during rotation leads to more rapid evaporation of the water and drying of the body. The clay may be somewhat finer textured as well, to avoid excessive abrasion of the potter's hands.

In throwing a pot on the wheel, the potter places a lump of clay on the wheel head with its mass carefully centered (fig. 8.9*a*), otherwise the pot will be asymmetrical and uneven in thickness. The clay is opened (fig. 8.9*b*) by inserting the thumbs or a fist into the center of the mass as it rotates. To shape the vessel, the potter lifts the clay (fig. 8.9*c*), aided by centrifugal force, with one hand inside and the other outside to draw the walls upward and outward, thinning them at the same time. Alternatively, in throwing "from the hump" a very large lump of clay is centered on the wheel head and several small vessels are thrown in succession from the clay at the top of the lump. Bases may be trimmed with a tool (fig. 8.9*d*) and finished vessels are usually cut from the wheel with a wire or thread while the wheel is rotating or stationary (for an unusual variant of completing wheel-thrown bases, see Dumont 1952).

The use of a wheel can usually be detected because vessels and sherds exhibit "rilling"—rhythmic ridges and grooves that spiral around the interior and exterior walls (fig. 8.10)—although these may be obliterated by careful smoothing of one or both surfaces. The undersides of the bases may bear characteristic concentric striations (e.g., fig. 5.3) caused by removing the vessel from the wheel while it is still turning.

Two related techniques are used to form vessels with molds fixed on wheels. In jiggering, used for plates, clay is placed over the convex curvature of a mold, which shapes the interior or upper surface, while a template is held against the clay to shape the lower surface or base as the clay and mold rotate; in jollying the clay is placed inside a concave mold and the template shapes the interior (Hamer and Hamer 2012: 194; Norton 1970: 143–44; Rhodes and Hopper 2000: 102). The procedures require

absolute centering of the mold and careful drying, especially of jiggered vessels. Jiggering may be performed by hand, but in industry it is mechanized (see, e.g., Schoen and Bleed 1993: 8–9, 16–18, 232).

Vessels may be manufactured in separate stages by combining construction techniques. In many instances the wheel's speed and momentum are not fully utilized, and the device is used more as a turntable (Nicklin 1971: 36). For example, vessels may be formed by molding the lower half and then coiling the upper portion; by throwing the body and adding a coil for the neck or rim; or by molding the base and throwing the body from coils, sometimes combined with beating, as in Musazi, Pakistan (Rye and Evans 1976: 32–34, pls. 18–26). Jars may be formed in two-part molds, the clay pressed into the molds while rotating on a wheel; after a short drying period a coil is applied to the opening in the top mold, and then the piece is placed on the wheel again to form the neck (Rye and Evans 1976: 33, pl. 22).

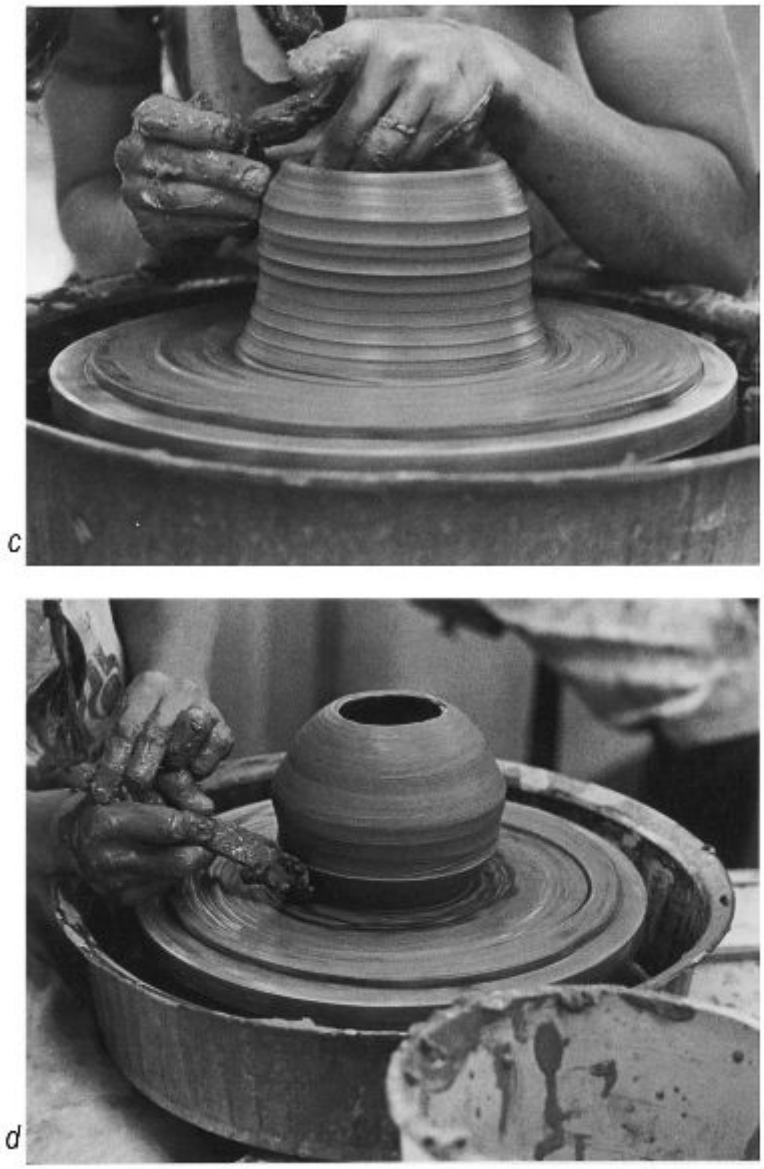

Figure 8.9 Throwing a pot on the wheel: *a*, centering the clay on the wheel; *b*, opening the lump of clay; *c*, lifting and thinning the walls; *d*, scraping to thin the base.

Modeling or molding is frequently used to shape decorative or functional appendages such as handles, spouts, or supports for vessels formed by any method. Partially completed vessels or preforms may be set aside to dry briefly (as in fig.8.6) while additional pots are begun, then the potter returns to the first pots and continues building by a different technique. In this procedure the potter must be careful that the edges of the preform do not dry excessively, and so the edges or the whole piece may be protected with cloth or leaves.

Figure 8.10 Rilling, the characteristic undulating ridges and striations running around the interior or exterior (or both) of a wheel-thrown vessel.

8.3 Finishing: Techniques and Tools

Between the various stages of construction, or after certain steps are completed, the vessels may be partially dried or partially rewet and subjected to various finishing procedures. Some of these, such as the use of a paddle and anvil, can be considered secondary forming techniques; they may alter the dimensions of the vessel as well as the surface characteristics. Other techniques affect the surface alone. The most important of these finishing techniques are beating, scraping, and trimming, which essentially complete the forming process, and smoothing and texturing to modify the surfaces.

8.3.1 Secondary Forming Techniques: Beating and Scraping

Beating or paddling—repeatedly striking the clay with or without opposing pressure—is employed on a roughly preformed vessel in the wet or pre-leather-hard stage. The most common technique uses a paddle and anvil (Bankes 1985; Fewkes 1941), in which a flat or slightly concave stick or beater is applied to one surface and a convex stone or clay anvil is opposed on the other surface (usually the interior). A series of rounded impressions (fig. 8.11) or faint facets may be left on the surfaces. Paddling or beating has significant effects on the final character of the vessel: it may improve the bonding of segments, obliterate coil marks or irregularities, compact the paste, and modify its shape, size, and surface characteristics by thinning the walls, altering or enlarging the contours, and smoothing (or roughening) the surface. Potters may employ several sizes, weights, or shapes of paddles in finishing a single vessel to vary the pressure or conform to its curvature (Fontana et al. 1962: 65; Ogan 1970: 87; Scheans 1977: 13, 50). Paddling is also used to create surface texture and decoration.

Paddling is commonly associated with finishing coil-built vessels, but the technique may be used with other construction procedures as well. Among the Papago, where pottery making is primarily a part-time activity of middle-aged women, most vessels (except ashtrays, toys, etc.) are formed by a combination of convex molding, coiling, and paddle-and-anvil shaping at all stages (Fontana et al. 1962: 58–79). In Guinhilaran, in the southern Philippines, both men and women make pottery, but each sex makes different vessels and uses different techniques. Men, for example, make flowerpots and large jars using a combination of techniques including slabbing, coiling, scraping, pinching, and paddling (Scheans 1977: 16–19). In parts of India and Pakistan, paddling is used on partially wheel-thrown jars to thin the walls and enlarge the vessel body (Dumont 1952: 81; Rye and Evans 1976: pl. 26).

Scraping is often described as the most time-consuming step in pottery manufacture; it may be carried out several times to thin the walls and remove surface imperfections. Commonly used to finish vessels built by coiling, molding, or pinching, scraping is usually done before the vessel has completely dried, while the clay is still wet and before it is fully leather-hard. Clay pastes having large inclusions usually exhibit linear

scars or ridges where particles were dragged along the surface in scraping, showing the direction of movement of the scraping tool. Scraping may be done with ad hoc tools similar to modern potter's ribs, such as modified sherds (López Varela et al. 2002) or pieces of cane, bamboo, gourd, shell, bone, metal, or hard plastic.

Trimming or fettling, usually associated with wheel-thrown or moldmade pottery, refers to cutting away excess clay and imperfections from the leather-hard vessel. For example, the ridge marking the join of two halves of a mold may be trimmed away with a knife or other sharp tool.

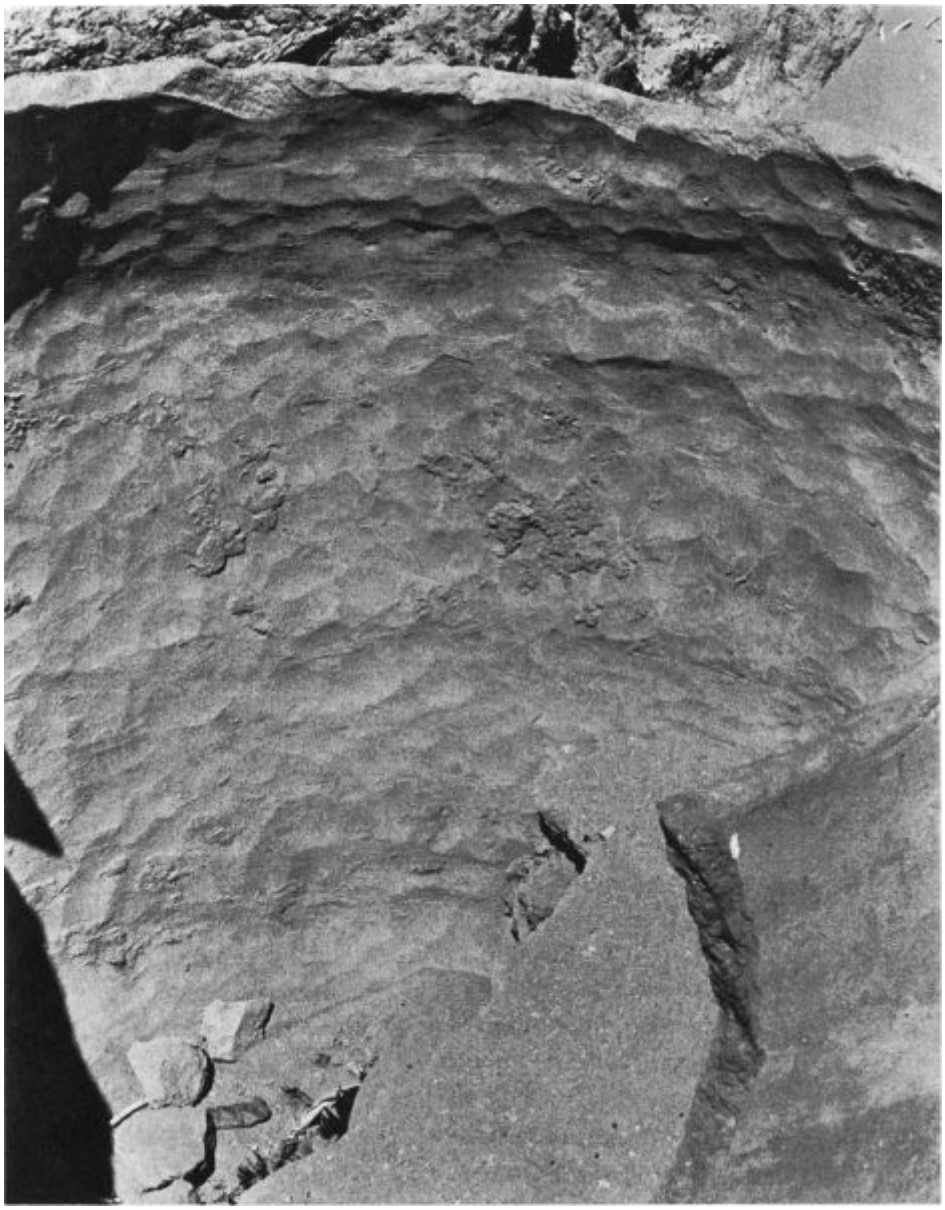

Figure 8.11 Characteristic shallow dimpling showing the use of an anvil on the interior of a wine storage jar in the Moquegua valley, Peru. These jars, measuring as much as 9 feet deep and 4.5 feet in diameter, with walls more than 1 inch thick, were made by segmental coiling followed by paddle-and-anvil treatment to compact the paste and shape the walls.

8.3.2 Surface Finishing: Smoothing and Texturing

Once the pottery vessel has attained its final shape and any irregularities have been eliminated, its surfaces are usually given some kind of finishing. This surface treatment may be cursory, or it may be time-consuming and precise; finishing may be the final attention given the vessel before firing, or it may be a prelude to additional decorative embellishment. The surfaces of vessels are often quick-dried in the sun before burnishing or decorating. For example, a Nasioi potter on the island of Bougainville dries her pots in the sun for six hours before smoothing (Ogan 1970: 88). The major surface-finishing techniques are variants of either smoothing or texturing.

8.3.2.1 Smoothing

A vessel is smoothed to create a finer and more regular surface than that resulting from the forming process. Smoothing is usually done by wiping the surface with a soft, pliant tool such as cloth, leather, a bunch of grass, or the potter's hand. Alternatively, a hard tool may be rolled over the vessel to eliminate imperfections and even out the surface; in highland Guatemala, for example, sticks and wooden spools are used on the pot's surfaces (Reina and Hill 1978: 135, 165). Vessels are usually smoothed before they are completely dry, or they may be rewet before smoothing. Visible traces of the procedure are a function of the texture (if any) of the material and the force with which it was applied. Brushing with a handful of grass, straw, or other lightly textured material may leave faint but irregular linear impressions. Similarly, where a wet hand smoothed still-plastic clay, the vessel often bears extremely fine, shallow parallel striations with rounded edges from the tiny ridges of the potter's fingerprints. The final surface has a matte rather than a lustrous finish because the particles are not well aligned or compacted; any luster is that natural to the clay.

In burnishing, a surface is finished by rubbing back and forth with a smooth, hard object such as a pebble, bone, horn, or seeds. This action compacts and reorients the fine clay particles (through plastic flow), giving a surface luster. This compaction with each stroke of the burnishing tool creates the narrow, parallel, linear facets that are the telltale mark of the technique (fig. 8.12*a*); careless burnishing produces an irregular, streaky luster (fig. 8.12*b*) and incomplete coverage. Burnishing may be done on leather-hard or dry clay but, except for clays with unusually low shrinkage or a high natural luster, the sheen will be retained only if the clay is burnished while dry. Luster can be destroyed with further shrinkage. Pattern burnishing creates a design by juxtaposing burnished (lustrous) and unburnished (matte) areas.

Figure 8.12 Burnished surfaces: *a*, the parallel facets on the surface of a burnished vessel marking the strokes of a hard tool, which compacts the paste; *b*, the uneven, streaky luster on a carelessly burnished and heavily fire-clouded vessel with appliquéd decoration.

A polished surface differs from a smoothed or burnished one primarily by execution: polishing is done by rubbing a dry surface with a soft material (cloth or animal skin) and gives a uniform luster without the parallel faceting produced by burnishing.

8.3.2.2 Texturing

Instead of being smoothed, all or part of the surface of a formed vessel may be textured, roughened, or patterned by striating, combing, stamping, impressing, and rouletting with various tools. These treatments may be applied to the entire surface of a vessel or to only limited areas—for example, striating the body of a jar and leaving the neck smooth, or applying the ends of hollow reeds to create a simple line of punctate circles on the

shoulder. In addition, the tools may be manipulated to create patterns such as undulations, bands, or checkerboards. In these latter cases the treatments seem to be primarily decorative (see sec. 9.1).

Textured surfaces may result from the construction technique, as in the coiled and "corrugated" vessels of the American Southwest, or from forming in a textured or patterned mold (e.g., a basket). Texturing is a common method of finishing vessels with utilitarian roles in cooking and transport, in which case the surface treatment also may be functional. Rough surfaces provide a better grip, for example, for carrying a heavy, wet vessel (Boulanger and Hudson 2012) and improve resistance to varying types of thermal stresses, such as retarding crack propagation (Schiffer 1990; Schiffer et al. 1994). To affect the final appearance of the vessel and to leave visible traces, these procedures are typically done when the clay is relatively wet and retains some plasticity, before it has dried appreciably.

Striating and combing are accomplished by drawing a toothed or serrated hard-edged tool, such as a shell or flaked stone, across the surface of soft or leather-hard clay (fig. 8.13). The strokes are usually done in the same (or nearly the same) direction, creating an overall effect of parallel, shallow scoring; sometimes the direction may be varied to create a herringbone pattern. If applied with sufficient force to significantly displace the clay, striating may also serve to scrape and thin the walls, and even the surface. Combing is a version of striating that may refer to creating groups of parallel striations, rather than complete coverage of the surface.

The techniques of stamping, impressing, and rouletting are not always mutually distinguishable, and the terms may be at least partially interchangeable. Overall surface impressing may be accomplished by rubbing or pressing with the edges of shells, fish spines, textiles, corncobs, nets, baskets, mats, or other materials. Surfaces may be finished by rolling or striking with stamps, cylinders or roulettes, or paddles made of carved clay, stone, or wood, creating individual or allover design motifs (e.g., Irwin 1974).

Figure 8.13 Interior of a sherd showing the striations left by scraping with an uneven or serrated tool such as a shell.

In rouletting, a common finishing technique in sub-Saharan Africa, a cylindrical tool is rolled over the surface, leaving a continuous impressed design. Designs may be carved in the wooden tool or produced by wrapping it with fiber strips or cords twisted, knotted, or braided into a pattern (e.g., Gosselain 2000). Variants of rouletting have been distinguished based on the size of the implement: *molette* (or roulette; 4 cm or less) and *rouleau* (roller; greater than 4 cm) (Balfet et al. 1983: 101).

In the eastern United States, stamped and impressed surface treatments continued into the ethnographic present. In addition to the items mentioned above, Pamunkey potters of northeastern Virginia also used "thimbles, railroad seals, watch chains, buttons, the denticulated edge of fossil sharks' teeth, the fluted surface of a muskrat's tooth, the end of a key, a string of beads . . . [and] glass pieces with flower designs cut on them" (Stern 1951: 21).

8.4 Drying and Preheating

The final step before firing is drying, sometimes with preheating immediately before firing. Nonindustrial village potters adjust their drying procedures to the characteristics of their clays and environment. For example, the time needed for drying is closely related to weather (see Arnold 1985: 65–70): in cool or rainy climates or seasons vessels take longer to dry, and potters in cold climates may risk having frost damage their wares. In such areas pots may be dried indoors in the home or workshop, sometimes near cooking fires or kilns to benefit from their warmth and preheat them before firing. Pamunkey (Virginia) potters dry their pots indoors on benches or shelves in their houses or in the smokehouse for not less than a week (Stern 1951: 26). Despite concerns about warpage during rapid drying, traditional potters may place vessels manufactured of relatively coarse pastes in direct sunlight, where they dry quickly without cracking. In the humid tropics, sun drying may simulate the humidity driers of modern industrial ceramics. Some potters in the Philippines dry their vessels in the sun for only one day after forming (Solheim 1952: 33); Bougainville potters may dry their pots in the sun for a week before firing (Ogan 1970: 88). Drying times may also vary (table 8.2) because of idiosyncratic or situational factors, such as waiting for enough pots to accumulate for a firing.

Table 8.2 Vessel Drying Customs in Sixty-One Ethnographic Situations

Drying Custom	Number of Cases
Time	
<1 day–2 days	13
2–5 days	17
Up to 1 week	14
1–2 weeks	9
2–4 weeks	6
1 month or more	2
Total	61
Location[a]	
In sun	14
Outside (general)	3
Shade or partial shade	10
Inside	16
Total	43

Source: After Arnold 1985: table 3.1.

[a] Some societies noted two locations of drying, while for others no location was given.

Preheating arrangements are most common in cool or damp climates or seasons, when pottery is often dried indoors. In the cool highlands of Guatemala, for example, vessels in Santa Apolonia are preheated in the potters' houses for as much as twelve hours before firing by placing them on a wooden rack suspended four to five feet above a slow-burning fire (Reina and Hill 1978: 63). Pamunkey potters start bonfires in their yards and place the pots near the blaze, turning them and gradually moving them closer until they are too hot to handle, at which point they are lifted onto the fire (Stern 1951: 27). A similar procedure is followed in Chinautla, with pottery to be fired in the late afternoon brought outside early in the morning to warm in the sunshine (Reina and Hill 1978: 39).

9 Surface Enhancement

> The potter's toolkit found in just one house or in a single burial will probably furnish more reliable behavioral information than a thousand factor analyses of house floor artifacts.
>
> Schiffer 1987: 21

Many "decorative" treatments can be applied to pottery surfaces to enhance their appearance, but decorative and decoration are difficult terms to define for pottery. Frequently presented as a false dichotomy against "functional" attributes, so-called decorative treatments may have varied functions (chap. 24), both utilitarian and symbolic. Certain surface treatments, such as the allover impressed or textured treatments discussed in sec. 8.3.2.2, or glazes and slips, are ambiguous: are they part of finishing or are they decorative? Also, certain kinds of decoration may modify the shape rather than only the surface of the vessel, and these secondary form characteristics may enhance the utility of the piece. Perhaps the verb decorate and its derivatives (decorative, decoration) are not only so imprecise but also so value-laden that they should not be used at all.

Nonetheless, these terms are used here for heuristic purposes. They refer to embellishments of pottery that are judged, usually subjectively, to be:

- Primarily for the purpose of enhancing the object's appearance or attractiveness;
- Relatively distinct from the procedures used in forming the clay mass into the final vessel shape and finishing its surface, and thus they may adorn only part of the vessel rather than the total surface; and
- Iconographic: icons (symbols, motifs, etc.) imbued with "meanings" that may be mythological, identity-related, and the like.

The decorative treatments discussed here may be differentiated on the basis of covering the entire surface of a vessel versus only particular parts; application before firing versus afterward; plastic techniques versus color applications; and additions to the surface as opposed to penetration. The decorative techniques are distinguished as those displacing or penetrating the surface and those involving additions to (or over) the surface. As with vessel construction techniques, these categories are not mutually exclusive and frequently several kinds of decoration are superimposed or applied to different parts of the piece (see Balfet et al. 1983: 19–25; Rye 1981: 89–94).

9.1 Penetration or Displacement

In displacement and penetration techniques, decorative embellishments are impressed into or cut from the surface. They may either remove or displace the clay, depending on how dry the object is. Impressing is usually performed on relatively wet clay, but cutting may be done on wet, leather-hard, or dry clay or even after firing.

9.1.1 Impressing

Impressing and displacing techniques include simple impressing, stamping, rouletting, rocker stamping, and punctation. These are similar to the techniques described as texturing, but as decoration they may embellish only part of the vessel rather than the total surface—for example, around the rim, neck, or shoulder or on an appliquéd fillet or flange.

Distinctions within this category depend on the object and method used to make the decoration. In simple impressing the imprint of a tool on the clay surface creates a pattern; the tool may be a natural object such as shell, reeds, corncobs, or animal teeth or bones, or it may be a manufactured item such as a piece of mat, textile, net, or string, or a carved cylinder (roulette) or paddle that, when applied to the clay, leaves a pattern. In stamping, a tool (any of those mentioned above or a specially formed die) is used to impress a repeated pattern of identical motifs. Stamping differs from simple impressing in the unitary rather than continuous character of the decoration. In rocker stamping, the convex edge of an object or tool, typically a shell, is moved over the surface by rocking from side to side, producing a distinctive zigzag decoration.

Paddling treatments are especially common in the eastern and southeastern regions of the United States, where the stamped designs may have iconic significance (fig. 9.1; see, e.g., Broyles 1968; Wallis 2006, 2011), and in coastal Peru (Cleland and Shimada 1994). Thus, if executed with a carved or wrapped paddle, the paddle-and-anvil technique also produces surface texturing. Southeastern Swift Creek stamped pottery may have been formed by women but stamped by men using wooden paddles they carved: this combination of female generative capacity and male structuring capacity "may have been an act of reproduction that paralleled human biological conception" (Wallis 2011: 202).

Punctation creates depressions in a wet clay, usually by poking with a sharp or pointed instrument such as a stick, a hollow reed, an awl, or a finger or fingernail (fig. 9.2*a*,*b*). This treatment is sometimes described as linear punctation if the depressions form lines. Punctation involves varying degrees of displacement of the clay.

Figure 9.1 A Swift Creek Complicated Stamped sherd showing overall surface texturing from beating the surface of a vessel with a carved paddle while still wet.

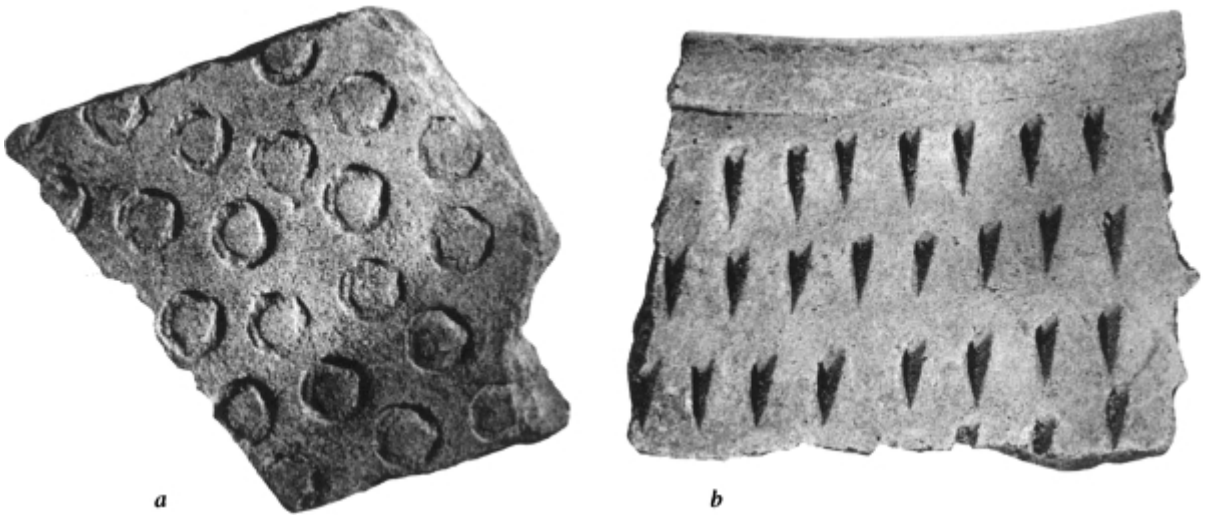

Figure 9.2 Punctation: *a*, with a hollow tube, such as a reed; *b*, rows of punctations made with a wedge-shaped tool.

It is often difficult to determine the exact tool or pattern used in these decorative treatments because of indistinct or overlapping impressions, the rough texture of the clay, or surface wear. Sometimes the motifs can be discerned more clearly by covering the area with Plasticine™ and studying the positive cast.

9.1.2 Cutting

Although both impressing and cutting techniques displace, penetrate, or remove material, in cutting operations the tool is drawn along the surface and through the clay. Cutting techniques fall into three major categories: incising, carving, and perforating. Most may be executed when the clay is plastic or leather-hard; some may be done when the clay is dry and some after firing.

Incising—cutting lines into the surface of a vessel with a sharp or blunt pointed implement—is one of the most variable of the decorative techniques. The appearance of incised decoration depends on the state of the clay (wet, leather-hard, dry, fired), the texture of the paste, the size and shape of the instrument, the angle at which the instrument is held, the pressure used, and the direction the tool is moved. Incised decoration may also be described in terms of when it is done, as preslip, postslip, or postfire. Postfire incising may be difficult to discern from dry paste prefire incising (fig. 9.3*a*), because both cause fine chipping of the clay or slip at the margins of the lines, creating a ragged edge. Incising wet or leather-hard paste, by contrast, leaves a clean line, sometimes with a raised margin from displacement of the wet clay (fig. 9.3*b*).

On the basis of these sources of variation, incised decoration may be further described by several terms (see Shepard 1976: 195–203):

- Fine-incising is done with a sharp-pointed instrument and creates lines that are narrow, are generally deep, and have a V-shaped cross section.
- Groove-incising may be done with an instrument that has a broader, rounded tip, and the lines are broad and shallow; sometimes it may be done by a gouge-like tool, held either perpendicular to the surface or at an angle.
- Preslip and postslip incising can easily be distinguished by whether the lines penetrate the slip or are covered by it.
- Prefire incising on wet clay may be distinguished from engraving, which is done on dry or fired clay (Balfet et al. 1983: 91, 95).

Carving refers to multiple cuts to remove clay from the vessel and create a design. Different kinds of carving are distinguished by the amount of clay eliminated and how it is removed:

- Simple carving is the cutting or gouging out of areas of clay, usually wet or leather-hard, to create a decorative pattern.
- Plano-relief carving, champlevé, and excising, on the other hand, refer to cutting out clay as the background for a design, which then stands in low relief. The surface—often slipped—is typically cut or

scraped away when the clay is dry or even after firing (fig. 9.3*c*). Of the three, excision is sometimes distinguished as involving only shallow scraping.

- Flat carving and modeled carving are usually executed in a leather-hard state, with the clay being deeply cut away, and then the design is further embellished by fine incising or modeling (or both) of the raised portions. Much of the carved black-and-red pottery of the Pueblo Indians in the American Southwest is of this type (e.g., LeFree 1975: 52–56, pls. 2–6).
- Chamfering is slicing away regular sections of the clay wall to create vertical or horizontal panels, often slightly overlapping like siding on a house.
- Fluting creates one or more shallow, broad grooves or channels in the clay, running either circumferentially or vertically (usually as multiple contiguous flutes).
- Gadrooning can be considered a variation on groove-incising and fluting: broad grooves are contoured by carving to create vertical segments that typically give round vessels a squash- or melon-like appearance. Vertical flutes also may create melon-like forms (see LeFree 1975: pl. 13).

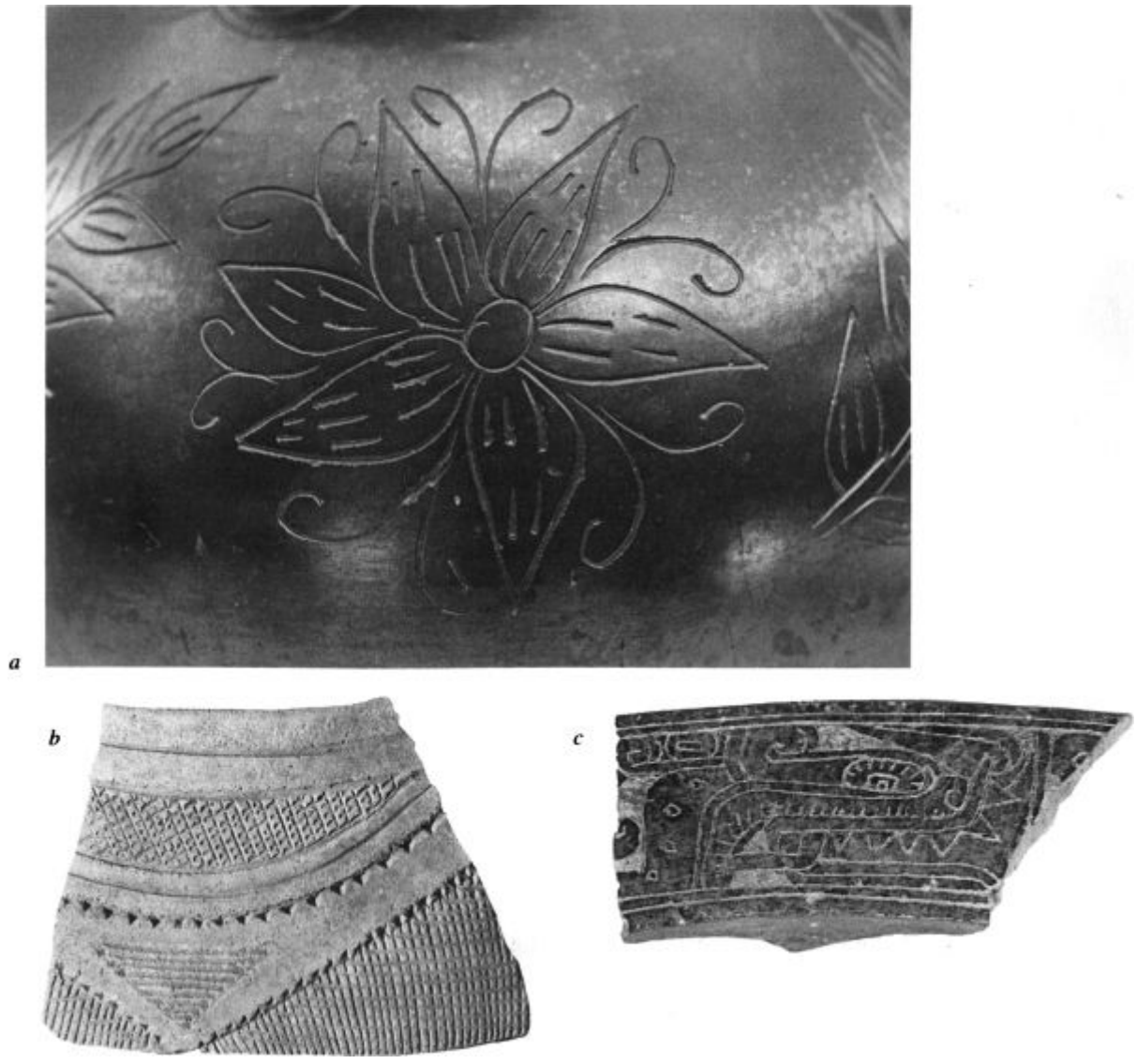

Figure 9.3 Incising and excising: *a*, postslip fine incising, done when the vessel was dry or nearly dry; note the fine chipping of the edges of the lines; *b*, fine incising done while the clay was still relatively wet; note the displacement of the clay along some of the lines, especially in the upper left; *c*, postslip (and possibly postfire) fine incising and excising.

Perforating and piercing refer to cutting through the entire vessel wall and removing portions of the clay, creating a lace-like pattern by a series of holes. The clay is usually plastic or leather-hard when this is done. Such containers may be more decorative than functional, as in the lustrous blackware produced in Coyotepec, Mexico, for use as dried flower containers and lampshades (Whitaker and Whitaker 1978: figs. 74, 75).

9.2 Additions to the Surface

A vessel may be decorated by varied additions to or over the surfaces, including formed clay elements joined to the vessel and treatments that alter its color. Any of these may be combined with the other or with the impressing and cutting techniques.

9.2.1 Appliqués

Decorative techniques based on joining include attached or appliquéd elements and adding decorative inlays. Appliqué refers to the attachment of small, shaped (modeled or molded) pieces of clay to the surface of the vessel (e.g., fig. 8.12*b*), such as fillets, pellets, spikes, and flanges. For best results the clay of the vessel and appliqué should be at roughly the same state of wetness, either leather-hard or plastic. The surface of the vessel where the appliqué will be joined may be rewet and roughened or scored, or the appliqué may be attached by luting, in which a small amount of fluid clay slurry or slip is used to promote adhesion. Instead of small decorative elements, the appliqués may be large and complex hand-modeled or molded attachments that are not only ornamental but also functional. Vessel supports (feet or bases), handles, or spouts may be elaborately shaped, often in natural or animal effigy forms, and attached to the vessel.

Decoration may also be achieved by inlay, in which small fragments of some nonceramic material, usually stone, are pressed into the clay to form a decorative pattern. Some jars made in Portugal, Spain, and Tunisia have inlays of small fragments of feldspar rock (see, e.g., Balfet et al. 1983: 124–25) and this inlay technique was carried to Mexico and Panama with Spanish colonial settlement.

9.2.2 Color and Colorants

In a second major category of decorative additions to a pottery vessel, color is the essential ingredient (for color measurement and reporting, see sec. 16.3). Two major types of surface coloration are common: those applied to only a portion of the total area and those that coat the entire surface. Vessel color can also be intentionally altered in firing, and firing variations can be elaborations on the other techniques.

Several terms are used to distinguish coloring constituents and functions, such as whether they are mineral or organic, and soluble or insoluble. The most inclusive term is colorant: chemical elements or "compounds that impart color to a substance" (Rapp 2002: 197). Colorants may be pigments or dyes:

- A pigment is a finely divided, insoluble coloring agent, either organic or inorganic, that is suspended in a medium (Rapp 2002: 197).
- A dye is a soluble organic substance that acts as a colorant for a material, such as indigo as a colorant (dye) for palygorskite or attapulgite clay in making Maya Blue pigment.

Pigments may be applied either before or after firing the vessel, although organic pigments frequently oxidize and disappear in firing. For application to pottery, these substances are usually mechanical mixtures of finely ground colorants (e.g., ochre), fine clay, water, and a binder. Clays slow the settling of the particles in the liquid mixture and enhance the flow and adhesion of the pigment. The vehicle or medium for the mixture may be water or an organic substance (resins, fats or oils, wax, urine) that aids in adhesion, the organic component oxidized and eliminated in firing. Potters in the Nicoya peninsula of Costa Rica, for example, add sour orange juice to their pigment to increase its adhesion to the vessel surfaces (Stone 1950: 272).

For unglazed, low-fired pottery, only three colorants naturally found in abundance (in oxide form) can survive the temperatures of firing: iron and manganese (pigments) and carbon. Black pigments may be produced by either iron-based minerals or organic materials (carbon), and they can be chemically distinguished by varied methods (Stewart et al. 2002). Carbon, applied in varied forms from powdered charcoal to plant extracts, can produce only a black or gray color and is typically added after firing. Papago potters in Arizona boil mesquite bark and add mesquite resin to create a postfire black pigment (Fontana et al. 1962: 77–78). Nicobar potters apply strips of unripe coconut husks to the sides and rim of fired pots while they are still hot to create black stripes; the husks are then wiped over the entire interior and exterior surfaces, imparting a light copper color (Man 1894: 25). A similar technique is reported for the Ibibio of Nigeria (Nicklin 1981b: 177). Organic material may be used before firing, either as pigment or as a binder mixed with other materials.

Other colorants may be applied to pottery after firing to highlight particular areas of a design. Among the Gisiga of Cameroon, kaolin is rubbed into grooved decorations (David and Hennig 1972: 6). Red minerals such as cinnabar (mercuric sulfide, HgS) and purplish-red specular hematite were occasionally rubbed into incised lines on various kinds of pottery in Mesoamerica (see, e.g., Backes et al. 2012).

9.2.2.1 Painting

Technically speaking, “paint” is a verb referring to the action of applying a colorant onto a substrate, such as a clay object, rather than to a specific kind of material. Painting may be done with a brush made of animal hair or fur, vegetal fibers, feathers, or similar material. Decoration painted in two colors is sometimes described as bichrome or dichrome; painting with three or more colors is polychrome decoration. Pigments generally adhere better if the vessel surface is dry when they are applied.

Several kinds of painted decoration are known:

- Glaze painting, in which painted pigments vitrify into a glass during firing, was known in antiquity in the Southwestern United States, with local galena (lead ore) as a flux (Creamer 2000; DeAtley 1986; Habicht-Mauche et al. 2002; Shepard 1942a, 1965; Thibodeau et al. 2013), and in the ancient Near East (Steinberg and Kamilli 1984).

- Postfire painting features certain pigments that are unstable if heated. For example, various sulfide and carbonate minerals, such as copper carbonates (malachite and azurite), will yield blues or greens. Yellows may be created from goethite or limonite. Graphite is a traditionally painted pigment for contemporary Phalaborwa potters in South Africa (van der Merwe and Scully 1971: 194), and in pre-Columbian times it was used as a painted pigment or slip in some areas of the New World.
- Resist painting (Shepard 1976: 206–12) and negative painting (Hilgeman 1985) are two similar techniques in which a design is created through application of a temporary protective coating over portions of the vessel surface that may be slipped or left plain. This coating is usually something organic, such as wax or grease, that will be removed by the heat of firing. When the organic material is eliminated, the design appears in positive or negative depending on its application. The decoration is typically relatively simple—wavy lines, dots, irregular blobs—and of a sort that is easier to apply with the coating than to paint around with a background colorant (see Shepard 1976: fig. 17).

The painted pottery of many ancient societies is renowned for its technical achievements and fills museum shelves and display cases the world over. Among the best-studied of these are the Greek black-figure and red-figure vases (fig. 1.5; Bimson 1956; Hofman 1962; Noble 1966; Richter 1976) and the various color *familles* (palettes)—green, yellow, rose—of painted Qing dynasty porcelains (Kerr 1998; Welch 2008). In the Western Hemisphere, the painted pottery of the Nazca (Proulx 2006) and Moche (fig. 1.7; Jackson 2008) cultures in the Andes has drawn considerable attention, as has that of the ancient and modern potters of the American Southwest (fig. 1.11; Hayes and Blom 1996; LeBlanc 2005; Plog 2003; Schaaf 2000).

Archaeologists, art historians, and others have studied the stunning human-figure polychromes of the Classic lowland Maya civilization of Guatemala, Belize, and Mexico (Reents-Budet 1994). Cylindrical vases for drinking *cacao* or *balche'* beer and serving plates are painted with complex scenes of kings and courtiers, animals and mythical figures (fig. 1.8), in royal courts or in the underworld, engaged in processions, holding audiences, dancing, recording tribute, and other activities. Brief formulaic glyphic texts may identify the owner of the vessel, its painter (usually a member of the royal elite), and the identities of the figures. Vessels were formed of clays tempered with volcanic ash or carbonate sand, covered with a light-colored slip, painted with various shades of red, orange, pink, and black, and then coated with a thin, translucent overslip. This overslip was probably composed of deflocculated colloidal-size particles and/or organic material (Rice 2009: 121). Vessels were fired at low temperatures, perhaps not much above 700°C, almost certainly in protective saggars of some sort, as they lack fireclouds. Additional postfiring pigments may be applied in colors of blue and green. Hundreds of neutron activation analyses (INAA) of the pastes of these and other polychromes, plus occasional recovery of workshop debris in "palace" structures, have indicated numerous production centers throughout the lowlands (e.g., Halperin and Foias 2010; Reents-Budet and Bishop 2003; Reents-Budet et al. 2000).

9.2.2.2 Slips

A slip (sometimes called an engobe) is a fluid suspension of clay (and other substances, such as colorants or a deflocculant) in water applied to an unfired clay piece to form a thin, nonvitreous coating (see Rhodes and Hopper 2000: 117–21). Studio potters often use the term terra sigillata as equivalent to slip, especially a red one, rather than a culturally specific kind of pottery. Slips are usually a different color than the body of a vessel, and may be applied for that reason alone, aside from their contributions to reduced permeability of the surfaces. White or extremely light-colored slips may serve a priming or sizing-like function in providing a smooth, clean surface for subsequent decoration and translucent slipping, as in the case of Classic Maya polychromes. If the clays are the same color as the paste and the coatings are extremely thin, they may be difficult to distinguish from unslipped, smoothed surfaces without a microscope or hand lens to reveal textural differences.

Slips exhibit considerable variation in color, quality, luster, and thickness, depending on the type of clay mineral present, the particle-size range, the kinds and amounts of adsorbed ions, and the degree of dispersion (flocculation vs. deflocculation) of the particles in the suspension. Of these variables, perhaps the most important is the kind of clay mineral present, for all the others are affected by this. Some of the most beautiful slips in antiquity—for example, those of Greek figured ware and Roman Samian ware—were composed of fine-textured illite clays.

There is no minimum percentage of clay content required to create a slip. In Santa Apolonia, Guatemala, cooking pots are covered with a thin slip-like paste of talc before slipping with a clay-based fluid (Reina and Hill 1978: 63). A similar slip-like coating of *tez* is used on tortilla griddles in nearby Mixco (Arnold 1978: 341); *tez* is a mixture of talc and chlorite, a phyllosilicate. In these coatings the talc (ground steatite; $3MgO \cdot 4SiO_2 \cdot H_2O$) acts like Teflon™ to prevent substances from sticking to the surfaces. The talc may also act as a mild flux (Rhodes and Hopper 2000: 144), fusing with and hardening the surface.

Slips may be applied by any of three techniques:

- Dipping a vessel in the slip gives uniform coverage, filling all holes, grooves, and irregularities in the surface. The vessel should be slipped in this manner while some moisture is still retained in the body.
- Pouring is used for vessels too large to be dipped or for vessels to be slipped only on the interior. Because of rapid absorption of the moisture in the slip, the pot must be turned smoothly and rapidly during pouring or the slip will be uneven.
- Slips also may be wiped onto the surface of a vessel with a cloth, a pad of grass or animal fur, or the potter's hands, but wiping frequently gives uneven coverage.

Slips may be applied over previous decoration, such as incising or appliqué, or various kinds of decoration—painting or incising—may be executed over or through the slipped surface (fig. 9.3*a*,*c*). Some slips have a high natural luster (a function of the type of clay mineral used), but most are burnished or polished to compact and orient the particles and impart a luster.

In slipping pottery the greatest problems occur in drying and firing: the slip and clay body may shrink differentially, so that the slip adheres poorly. For this reason, slips on low-fired pottery are usually applied to completely dried wares, often immediately before firing, and carefully burnished for better adhesion. If the slip and body have markedly different coefficients of expansion, the slip may craze or flake ("shiver") during or after firing. Some slips may actually be "tempered": whether this is to improve fit (as in some Maya slips; Shepard 1962: 253) or to enhance the cooling properties of water jars, as suggested by potters in northwestern Pakistan (Rye and Evans 1976: 53), is not always clear. In addition, if the slip is fired to too high a temperature, firing shrinkage may destroy its luster. The uneven compaction of the clay particles in careless burnishing occasionally results in slight color differences between burnished and unburnished areas; this is especially true in areas of fireclouding (fig. 8.12*b*).

Slips, especially thin slips, may be applied in several coats, as at Santa Clara Pueblo (LeFree 1975: 40–44), for better coverage of the body. Santa Clara potters enhance the bonding qualities of their slip by adding an organic glue or adhesive: after burnishing the two coats of slip, they coat the pottery with grease, allow it to penetrate, then polish the vessels with a chamois cloth before firing.

Three additional terms are fairly common in the literature to designate coatings that are variants of slips:

- The terms self-slip and floated surface are sometimes used for finely textured surfaces that appear to be slipped with the same material as the clay body. The presence of a distinct slip is difficult to determine, and in some cases this effect could result simply from carefully wiping the surfaces with a wet hand, which brings the finest particles of the paste to the surface and may orient them. Like separately applied slips, these thin coatings might still have an effect on reducing surface permeability (Cotkin et al. 1999).
- A wash usually refers to a separate postfire coating of the surfaces; this may be a pigment or a lime-based stucco and may subsequently be painted. The major distinction between a wash and a slip is that a slip is applied before firing and a wash is applied after firing.

9.3 Glaze

Glazes (chap. 7) are applied to pottery for the same reasons as slips—to add color and reduce permeability. They differ from slips because they are high-fired and glassy, they make the surface completely impermeable, and they are compositionally complex. Ceramic glazes may be shiny or matte, translucent or opaque, low-fired or high-fired, colored or clear, thick or thin, and occasionally they may be formulated to (re-)develop a crystalline structure (see Hopper 2009; Lawrence and West 1982: 173–99; Nelson 1984: 190–263; Rhodes and Hopper 2000).

The ingredients for the glazes used by traditional potters often come from nontraditional sources. In Quetta, Pakistan, for example, the silica for the glaze comes from glass cullet, waste products of window-glass cutting or broken bottles purchased from the bazaar; manganese comes from the crushed cores of old dry-cell batteries also purchased there (these batteries also contribute aluminum and zinc); and copper is obtained from copper scale, produced by heating sheet copper to red heat, quenching it in cold water, and then scraping off the black fire scale (Rye and Evans 1976: 74). Flour and water are boiled for several hours, making a thick binder solution to which the glaze ingredients are added (Rye and Evans 1976: 74).

Some glazed wares are covered, before or after the bisque firing, with a slip or an engobe, a term that is less common in archaeology and tends to be used primarily with reference to high-fired ceramics. Engobes are intended to alter the color of the vessels and are usually white; their ingredients are selected to ensure low shrinkage and good fit with the vessel body. They are then covered with a clear glaze, such as a lead glaze. A particular type of decoration associated with slipped and glazed wars is called sgraffito: a technique of incising through a slip or engobe before glazing. The cut lines expose the paste and contrast in color with the areas covered by both slip and glaze.

Decoration on the tin-glazed or tin-enameled wares of early or proto-majolicas began in the Islamic world with copper green and manganese purplish-brown; centuries later brilliant blues, yellows, oranges, and metallic luster pigments were added. Typically the ware was given a bisque firing, then covered with the enamel and the decoration painted over the glaze. Because the unfired dry glaze is powdery and absorbent, making the brushwork of painting very difficult, these enamels may have had sugary binders added to them, which form a slight "crust" during drying (Rhodes and Hopper 2000: 264). Manufacturers of Talavera majolica-style pottery in Puebla, Mexico, add honey to the glaze as a binder (Whitaker and Whitaker 1978: pl. 3). The piece is then given a second firing during which the decoration fuses with the glaze (see Thornton 1997: 119). Today's majolica decoration is typically described as "onglaze," meaning that the pigments are painted over an already-fired glazed surface and the object is refired at a lower temperature (Hamer and Hamer 2012: 241). Italian wares were often given an additional clear glaze *coperta* or covering over the painting.

10 Firing

> A big kiln firing has the aspect of a battlefield where men test themselves to the utmost against odds.
>
> Leach 1976: 196

The pyrotechnologies associated with non-industrial pottery-making, ancient and recent, can be categorized in several ways. As more is learned about traditional firings and structures, the usual differentiation between open or bonfire firing and firing in a kiln structure is difficult to maintain: firing technologies demonstrate continua of degrees of enclosure and other variables, rather than a distinct binary of presence/absence. Here I use a slightly different but related characterization based on the relative positions of the fuel and the wares being fired, as mixed/intermingled and separated. The latter is typically associated with firing in facilities usually referred to as kilns. Both schemes highlight an important functional difference: separation of the fuel from the ware in an enclosed chamber permits better control of rate of heating, more sustained soak temperatures, and the use of glazes.

Although built structures for firing began to be used millennia ago, in most areas of the world throughout antiquity and in many areas during modern times pottery has been successfully fired in the absence of formal kiln structures. And as more evidence of varied firing strategies has been accumulated by archaeologists and ethnoarchaeologists —especially in Africa (e.g., Gosselain 1992; Smith 2001)—along with growing identification of pre-Columbian firing facilities in the Western hemisphere, the sharp dichotomization between kiln and non-kiln firing is no longer appropriate. The varied techniques have advantages and disadvantages in terms of the final products and the costs to working potters (see Thér 2014). And, importantly, in many places multiple firing techniques were used contemporaneously.

10.1 Separated Fuel and Ware: Kiln Firing

Kilns are chambers, partly or completely enclosed, that contain combustion, provide a stable setting for ceramic wares, and channel heat during a ceramic firing. They have three main components: a firebox (or mouth) to burn fuel and generate heat; one or more ware chambers to hold the pottery and retain the heat; and one or more flues that permit hot gases to escape and create a draft to move the heat from the firebox through the ware chamber(s) (Rhodes 1981: 21). Kilns past and present have been classified in many ways, primarily on the basis of industrial uses and products (table 10.1).

Table 10.1 Firing Arrangements Based on Relative Positions of Fuel and Ceramics

I. Fuel and Ware Separated (Kilns)
  A. Continuous
    1. Annular—for bricks
    2. Tunnel—for bricks
    3. Rotary—for tableware
  B. Intermittent (periodic or "batch" kilns)
    1. Downdraft
    2. Updraft
    3. Round—heavy clay or refractories
    4. Rectangular—heavy clay or refractories
    5. Bottle—coal-fired, for pottery
II. Fuel and Ware Mixed
  A. Open
  B. Pit
    1. Pit
    2. Trench

Source: From Rice 1997b: 3–5.

Kiln structures represent a major advance toward ensuring success in firing pots, the most dangerous final step of the potter's enterprise. Kilns permit better-controlled temperatures and atmosphere, protect the vessels from drafts, and provide a boundary to enclose the heat. Although it might seem that the main advantage offered by kilns is more efficient use of fuel, fuel conservation, or higher temperatures, it appears from ethnographic and experimental studies that the primary advantage is control of the *rate* of heating (Gosselain 1992: 257; Pool 1997: 166; Rice 1997a: 253; Smith 2001). Kiln structures were widely used throughout the Old World in antiquity, but in the New World above-ground kilns had a restricted distribution until the arrival of European ceramic technology in the early sixteenth century (Rice 1997b).

10.1.1 Types of Kilns

Above-ground, freestanding kilns are constructed of refractory material, usually brick, which is able to withstand the stresses of continual expansion and contraction in firing and cooling. Few kilns used in antiquity or by today's traditional potters, however, are the permanent, highly refractory installations used in modern noncommercial and non-industrial settings. Instead they are often impermanent, constructed of adobe and requiring frequent rebuilding, in whole or in part, because of thermal stresses or overheating (e.g., Rice 1994: 331–37). Sometimes kilns may be constructed partly or entirely of stone, as in Pereuela, Spain (Peacock 1982: 21), or reinforced with stone, as in Peru (fig. 10.1).

Figure 10.1 A large round updraft kiln at Yahuay, an abandoned winery in the Moquegua valley of Peru. The lower exterior is reinforced with rounded river stones, while the major construction is of adobe brick. The three openings for introducing firewood into the chamber are not visible in the photograph. Note buttresses left and left center and the cracks near the top of the structure.

Two basic types of kilns can be identified based on the physical relations between the wares and the source and movement of heat: updraft and downdraft (see Cardew 1969: 170–212; Leach 1976: 178–97; Nelson 1984: 21–24; Rhodes 1981).

Updraft kilns are simple enclosed firing chambers in which the heat moves upward from underneath the pots and then is vented outward. Fuel is fed through a firebox, often excavated into the ground, below and forward of the firing chamber, or through openings in the side of the kiln (fig. 10.2). A perforated platform of clay or brick acts as the floor of the ware chamber to allow the flames to penetrate from the firebox up to the pots. Heat and gases escape through the top of the kiln, through either a chimney or openings in a temporary covering. Very early updraft kilns were often bank kilns dug into the side of a hill or embankment (see fig. 1.3), with the firebox at the lower level, the firing chamber immediately adjacent, and a vent or chimney leading up and outside. Above-ground updraft kilns are usually cylindrical for pottery firings (fig. 10.1) but square or rectangular for firing bricks.

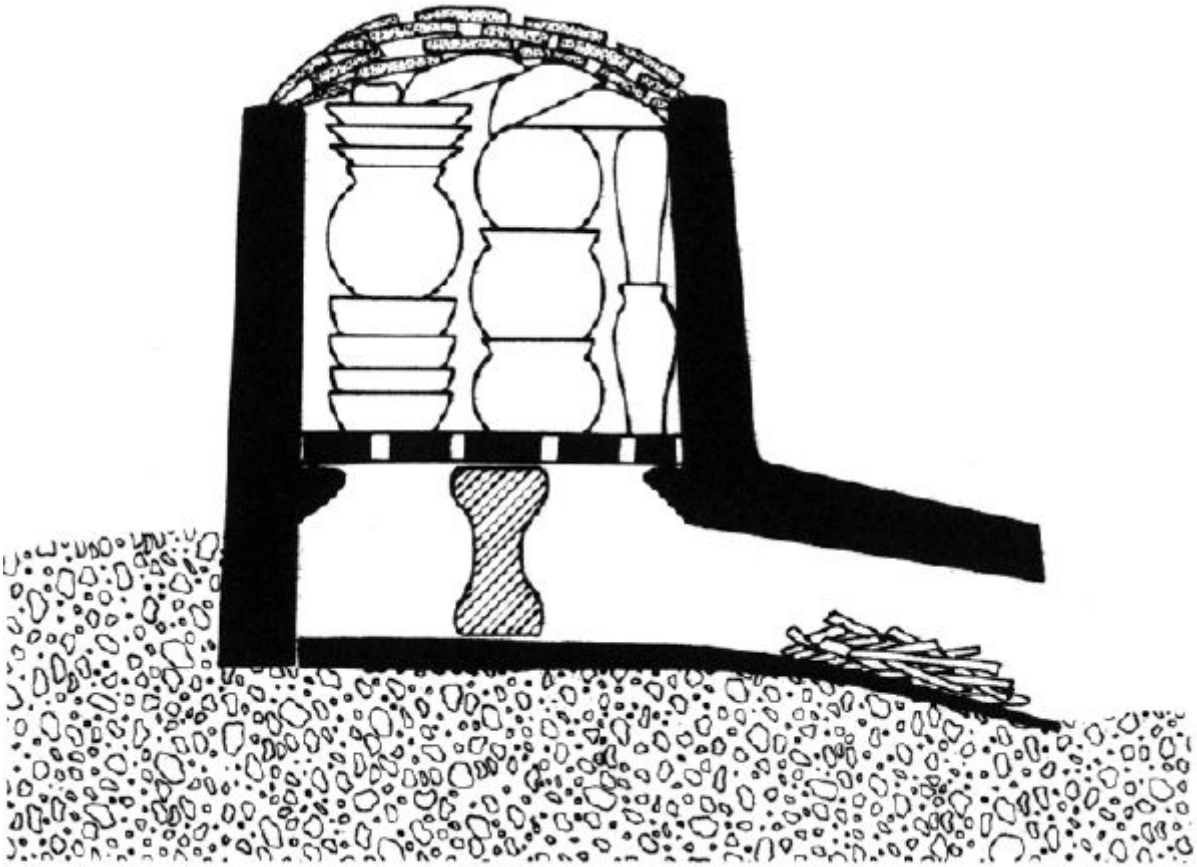

Figure 10.2 A simple open-topped updraft kiln, with sherds used as a temporary cover.

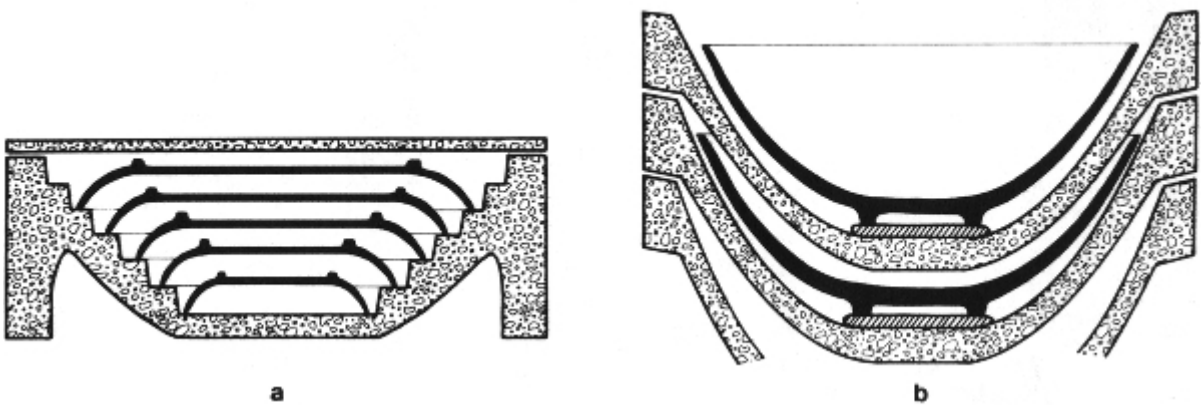

Figure 10.3 Two versions of saggars (or "setters") from China. After Medley 1976: 109.

The most common updraft kilns are simple, circular, freestanding structures with open tops. The kiln is loaded for each firing from above, with the setter often standing on lower tiers of pots (assuming considerable green strength) to position the successive layers. The pieces to be fired, glazed or unglazed, may be placed inside protective containers called saggars (fig. 10.3) or stacked and carefully separated by small tripods called stilts or props so that they do not touch each other. The opening may be closed by placing a layer of large sherds (or flat griddle-like articles to be fired) over the load, or

a temporary domed roof may be created with mud or by setting bricks in a series of courses angled inward until the top is almost sealed. The maximum temperature these kilns attain is usually 900°C to 1000°C. In fully enclosed kilns, the atmosphere may be controlled by the selection of fuel and by regulating air circulation.

Although updraft kilns have numerous advantages over open fires in terms of containing and sustaining the heat, there are several disadvantages. A considerable amount of rising heat escapes unused through the top of the kiln. Also, hot spots or conduits of heat ("chimneys") are often created by the placement of vessels in the kiln, so that parts of the load may be overfired and other parts underfired. In addition, vessels at the bottom of the kiln load, which receive the direct heat of the fire, may suffer thermal shocking.

Simple updraft kilns have been excavated in pre-Columbian Mesoamerica, primarily in Mexico (e.g., Abascal 1975): more than two dozen have been dated to the Terminal Formative period at Monte Albán in Oaxaca (Elson and Sherman 2007; Payne 1982; Winter and Payne 1976) and thirty-six Classic-period updraft kilns constructed of fiber-tempered adobe were identified at Comoapan in Gulf coastal Veracruz (Arnold et al. 1993; Pool 1997; Santley et al. 1989).

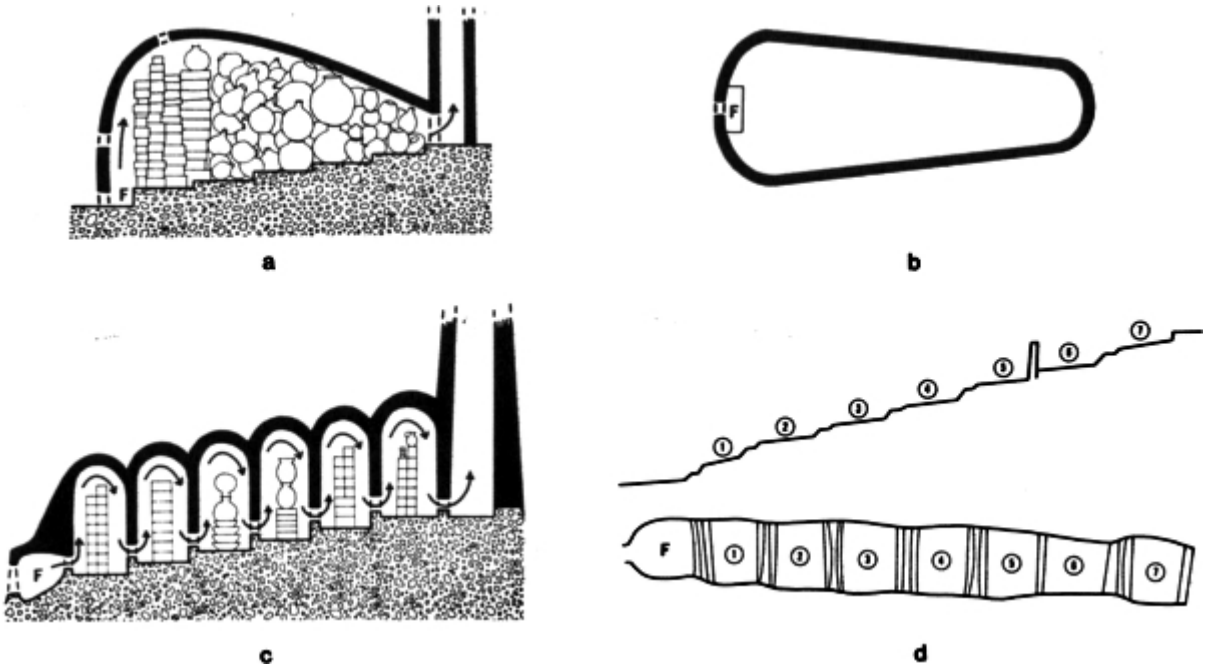

Figure 10.4 Kilns: *a*, *b*, large, single-chamber climbing bank kiln similar to those used at Jingdezhen; *c*, Longquan multichamber climbing kiln; *d*, plan of ruins of Old Karatsu multichamber climbing kiln, dating to the sixteenth to seventeenth centuries. F indicates firebox. Sources: *a*, after Nelson 1984: fig. 24; *b*, after Leach 1976: 183; *c*, after Medley 1976: 148 and Nelson 1984: fig. 25; *d*, after Mikami 1979: fig. 166.

Downdraft kilns differ from updraft kilns in the location of the vessels to be fired relative to the movement of the flames and the heat of combustion. Whereas in updraft kilns the heat moves upward through the kiln load, in downdraft kilns it is deflected from direct contact with the pots by a bag-wall and forced to travel upward in the kiln.

It then passes down through the chamber holding the pots and is vented outward through an exterior chimney assembly, which also provides most of the draft. Downdraft kilns have several advantages: more of the heat of combustion is used because the downward draft through the kiln counters convective heat loss, and the downward currents discourage chimneys of intense heating.

A variant type of kiln is known as a tunnel or climbing kiln, and these may operate on updraft or downdraft principles. Used in many parts of East Asia including Japan, Korea, and China, climbing kilns consist of a long, tunnel-like ware chamber or a series of linked chambers built on a slope. Firing begins at the base of the slope, with fuel supplemented at points along its extent, and the gradient provides the draft for combustion (fig. 10.4). Exterior openings in the chambers permit setting pots, adding fuel and admitting air, and viewing the vessels as they fire. In multichambered kilns, such as the semi-continuous downdraft kiln, the heat and flames enter each chamber at its base, are deflected upward, then circulate down through the pots, out at the rear base, and into the next chamber. Extremely large kilns may have as many as twenty chambers and take two weeks to fire (Leach 1976: 186).

10.1.2 Firing

Kiln firings are lengthy and high temperatures are achieved gradually. The slow rate of heating to high temperatures is in part an accommodation to the temperature differential, or thermal gradient, between the surfaces and interior of the clay walls of a ceramic piece (see fig. 6.3). Different physical and chemical changes are taking place at different times within the clay, which can set up damaging stresses. A description of firing a traditional potters' kiln comes from Vounaria, Greece, where potters use simple cylindrical updraft kilns with a conical vaulted roof and fire about once a week during their working season from April to October:

> The potters are skilled in loading their kilns so that they effectively use the space, so that there is little damage from the simultaneous firing of unglazed and glazed ware, and so that the flames and hot gases of combustion can flow freely around the kiln load in ways that will result in quite a uniform heat distribution. . . . Water jars (*vikes*) are first placed in the kiln to a depth of about 0.6 m. Above them are *stamnes* [amphoralike jars] which, if this is their second firing, have glazed interiors and a glazed exterior shoulder and rim zone. Vikes are again used to top the load. Thus the glazed ware is to some degree protected from the direct impingement of the flames, and may possibly be exposed to a slightly lower firing temperature. . . . The ware is usually stacked in the kiln upside down to prevent ash accumulation in the vessels and, for the glazed ware, to maintain a thick glaze on and near the rim as well. Roof tiles are used as dividers and supports in loading the kiln, as also are large sherds from broken pieces. A kiln load of medium-sized and small vessels consists of about 700 pieces. . . .
>
> The firing begins very slowly, which is normal good ceramic practice. Throughout the 7–10 hours of the operation, fuel is added constantly in short pieces. . . . The fuel used at Vounaria varies according to what is available and how much it costs. The generally preferred fuel is *verga,* prunings from the vineyards, for the vine clippings burn well and do not build up a bulky mass of glowing slow-burning charcoal. . . .
>
> The end of the firing is determined in Vounaria by the kiln color of the pottery in the bisque firing, or by the quality of the glaze in the glost firing. Often glazed and unglazed ware are fired together. When the incandescent pottery looks "white" in the kiln, the proper temperature has been reached and the firing is

finished. Judging from laboratory experiments, this will be at about 900° plus or minus 50°. . . . The kiln is then allowed to cool from two to four days, depending upon its size, the exterior temperature, and the immediate need for the fired ware to supply a trucker who has come to purchase it.

(Matson 1972: 218–20)

10.2 Intermingled Fuel and Ware: Mixed Firing

Mixed firing arrangements vary considerably, depending on the nature of the potting tradition and local resources, but they share certain general characteristics. A bed of fuel (often fairly slow burning) is prepared directly on the ground surface or on a layer of ash or sand to retard the penetration of soil moisture. The pottery to be fired is positioned over the fuel, and more fuel (the same kind that constitutes the original bed or else a faster-burning kind, or a combination) is placed around, among, and on top of the pottery. The fuel is ignited, usually beginning with the lower layer (fig 10.5*a*); sometimes it is allowed to begin to smolder while the pots are being placed. Additional fuel is added (fig. 10.5*b*), and after a while the fuel burns itself out.

Fuels used in mixed firings are highly variable, including agricultural by-products (corncobs or cornstalks, sugarcane, grapevines), bamboo, bark, branches, brush, charcoal, coal, coconut husks, dung, grasses, palm fronds, straw, and wood. Hardwoods burn hotter and longer than softwoods and generally with the preferred cleaner flame, although the resins in pine can contribute to high temperatures. The placement of the fuel under, over, and among the pots being fired may damage them, because they are in direct contact with the flames and may shift when fuel is consumed. Vessels must be carefully positioned to ensure maximum stability.

One kind of mixed firing is the open bonfire. Large chunks of fuel (e.g., dung cakes), sherds, metal, or other protective devices such as basins or grates may be arranged around or atop the vessels to partially enclose them and to aid in retaining heat, as in Santa Clara, New Mexico (LeFree 1975: 58–60). A single pot may be fired in the open, or a large arrangement of several hundred carefully stacked items several feet high may constitute the firing (fig. 10.6). Shipibo-Conibo potters fire small vessels in a saggar-like bottomless vessel (DeBoer and Lathrap 1979: 120). The fired ware may be removed almost immediately or allowed to cool before being removed from the ashes (fig. 10.5*c*).

Semi-subterranean variants of mixed firings take place in shallow excavated depressions, trenches, or pits; this was the original definition of "mixed firing" (Rye and Evans 1976: 164–66). Functionally, these may be considered intermediate between open firings and updraft kilns in that they partly enclose the fuel and ware, but the fuel and ware are not typically separated. Instead, the fuel is usually spread around the pots as in open firing. For example, trench firing facilities in the Southwestern United States are rectangular areas varying from 1.5 to 8.5 m in length and 0.8 to 2.0 m wide, excavated to a depth of 10 to 65 cm (Blinman and Swink 1997: 88). The sides are typically lined with vertical slabs of sandstone and the floor is stone-paved. Residues indicate that pine and juniper were the primary fuels, perhaps supplemented with corn stalks. Given their location as much as 5 km from residential areas, the trenches may have been sited to take advantage of good fuel sources. Their size suggests that they

might have held as many as 150–200 vessels at a time, primarily beautifully painted black-on-white ware, which might represent the output of several potting households (Bernardini 2000).

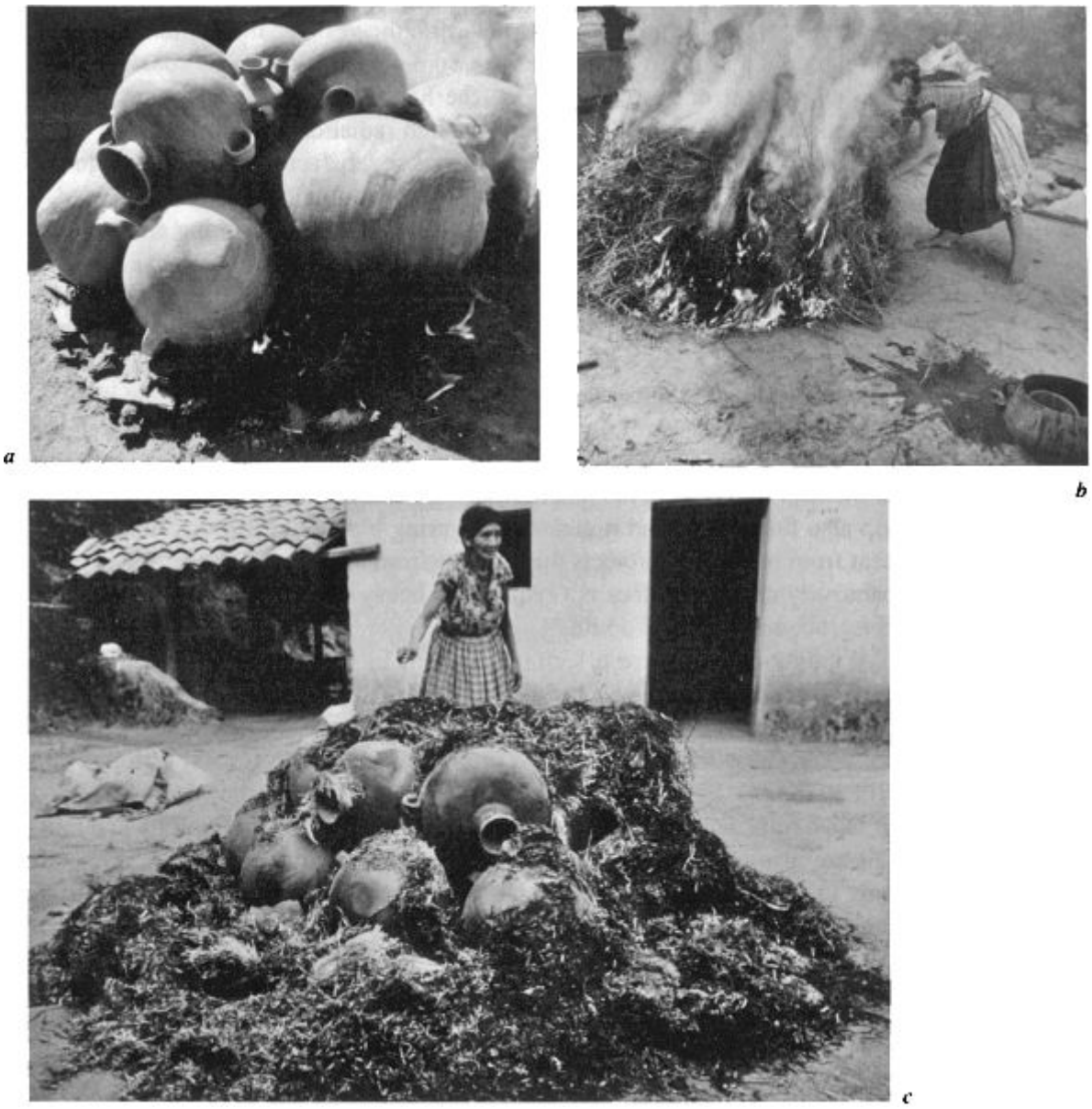

Figure 10.5 A bonfire firing of water jars in the courtyard of potters in Chinautla, Guatemala: *a*, Pots are placed over a layer of pine bark and dung, which has been ignited with a few coals. *b*, When the pots begin to turn black, the pile is covered with straw, which burns very rapidly. *c*, The thick layer of ash after firing is gingerly poked away soon after firing, and pots are exposed to the air while still hot (at the time this photograph was taken, there was still a dull red glow to be seen in the center of the pile of pots and ash). The firewood to the left is for cooking, not for firing pottery.

Firing pits (fig. 10.7) sometimes are multichambered with separate areas for ware and fuel. They typically consist of one or more round or elongated excavated chambers of varying depth, but they are horizontally rather than vertically arranged, with no protective barrier between them. Fuel is placed below, between, and above the pots, and the assembly is fired in much the same way as open firings. Pit- or trench-firing

features constructed on a slight slope may, like bank kilns, take advantage of the gradient to move the heat through a firing load (Rye and Evans 1976: 41). Various kinds of pit-firing arrangements have been excavated in Mexico and Peru. In highland Oaxaca, Mexico, single- and double-chambered subterranean firing features may date a little more than two thousand years ago. In the far southern Oaxaca valley at Ejutla, shallow firing pits with irregular dimensions were excavated 40–70 cm into bedrock, with extended mouths opening toward the prevailing afternoon wind (Feinman and Balkansky 1997: 139; see Balkansky et al. 1997). In Peru, single- and double-chambered firing pits on the north and central coasts date back as far as the early first millennium BC (Shimada 1997; Shimada et al. 1994; Shimada, Goldstein, et al. 2003).

Figure 10.6 Potters in Gogunda, Rajasthan, India, rushing to begin a firing of various sizes and shapes of cooking pots before the rains start during the monsoon season. Many firings involve 800–1000 vessels at a time. Note how fuel is inserted into the mouths of vessels encircling the base of the open setting. Once the firing has commenced, sawdust and a layer of ashy earth are placed over the pots to create a smudged blackware. Pots are removed from the pile the day after firing. Photograph by Carol Kramer.

Because the heat in firing pits is partially contained, these arrangements may achieve higher temperatures or sustain them longer than completely open bonfires (see, e.g., Shepard 1976: fig. 4). Maximum temperatures may be in the range required for the maturing of glazed wares, but mixed firings in pit features are generally used for

nonglazed terracottas and earthenwares. Most of the disadvantages of fully open firings, such as poor control of temperature and atmosphere, also hold true for pit firings.

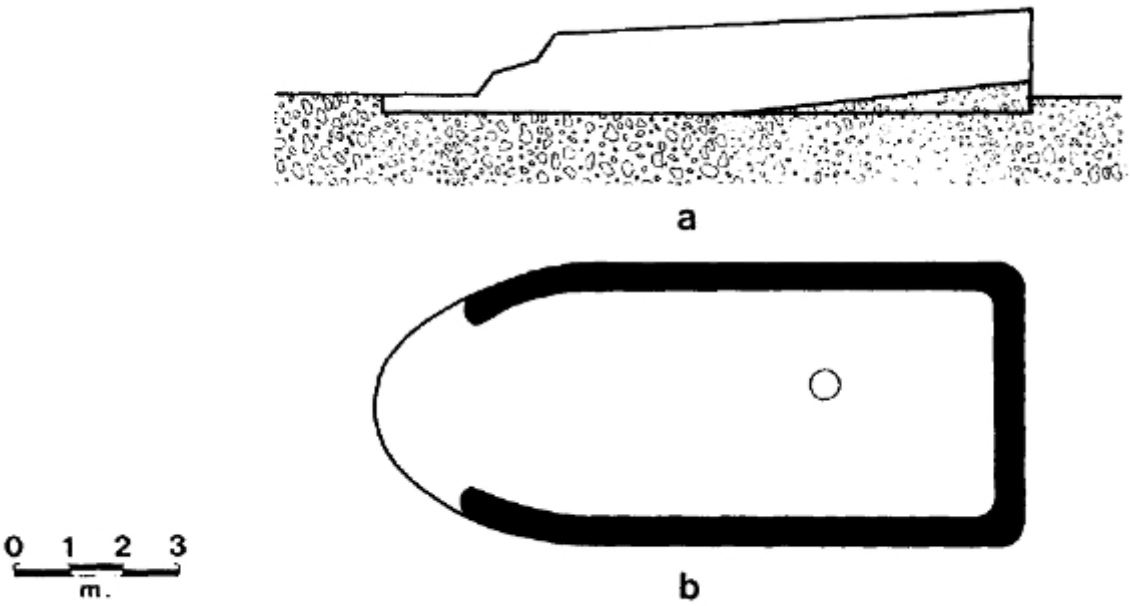

Figure 10.7 Open pit kiln at Musazi, Pakistan: *a*, cross-section; *b*, plan—circle indicates size of large water jar for comparison. After Rye and Evans 1976: fig. 7.

10.2.1 Time, Temperature, and Atmosphere

The most striking characteristic of the various kinds of mixed firings is the extremely rapid and generally poorly controlled rise in temperature. Firings are typically short and achieve relatively low temperatures of 700–900°C (Smith 2001: 997). The maximum temperature attained, the time necessary to reach it, and the duration of high-temperature burning or soak are functions of the kinds of fuel used and its size, quantity, and positioning (Shepard 1976: 77–91). The highest temperatures are usually attained at or just after the fuel covering the pile of pots has been consumed. These generally range between 600°C and 850°C, but there is considerable variation, and temperatures of 900°C or more are not uncommon. Such maxima have been attained in open firings with dung, coal, juniper wood, and palm fronds, and can be reached within twenty minutes (fig. 10.8; Colton 1951; Nicklin 1981a: 352, fig. 32:2; Shepard 1976: and 5, table 3; Smith 2001). A minimum temperature of 550°C should be attained to make serviceable pottery, according to Michael Cardew (1969: 11), but one might ask, “serviceable” for what? Indeed, because of clays’ chemical and physical variations it can be questioned whether an absolute minimum temperature can reliably be specified at all.

The rate of combustion of fuel is affected by the ratio of its surface area to weight, because this determines the availability of oxygen. Large pieces of fuel, such as logs,

burn slowly whereas finer matter, such as wood chips, shavings, or grasses, combusts more rapidly because of the abundant surface area available to oxidize. For this reason the slow-burning fuel usually underlies the vessels, and provides most of the sustained heat for firing. At the end of combustion the finer fuel above creates an insulating layer of ash over the vessels that helps retard convective heat loss from below and protects the hot pots from wind gusts. There is some variability in the rate of burning of dung—Shepard (1976: 77) considers it to be fast burning, while potters in Pakistan regard it as slow burning (Rye and Evans 1976: 165)—and this doubtless varies from animal species to species. (See Sillar 2000 for a thorough discussion of dung as fuel for pottery firing; see Winterhalder et al. 1974 for discussion of dung as fuel for cooking fires.)

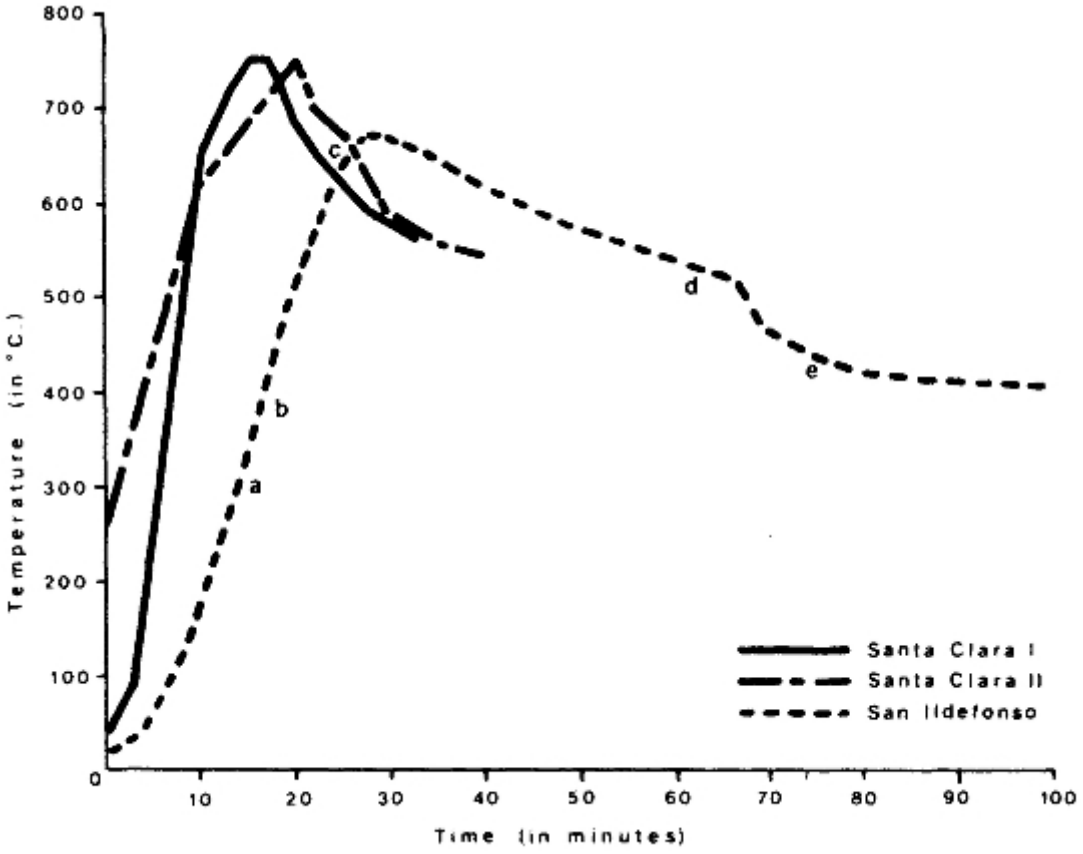

Figure 10.8 The rapid schedules of three Pueblo firings of smudged ware: *a*, *b*, adding dung and juniper chips; *c*, smothering the fire with powdered manure; *d*, removing protective sheets of tin; *e*, bonfire heap covered with ashes for additional smudging. After Shepard 1976: fig. 6.

Given these fuel-related considerations, it is not surprising that the duration of open firings is highly variable. Although they typically last only a few hours from starting the fire to removal of the pots, these firings sometimes take up to eight hours, as among the Pamunkey of Virginia (Stern 1951). Elsewhere, they may last only fifteen to twenty minutes (David and Hennig 1972: 6; Longacre 1981: 60; Nicklin 1981a: 348; Scheans 1977: 45; Shepard 1976: table 3).

Not only are the time and temperature of bonfire firings poorly controlled, but so is the atmosphere. Variations may be expected as fresh fuel is added and irregularly consumed, as smoke is produced, as gases are released from the fuel and the pottery itself, and as wind gusts touch the fire. Thus the atmosphere is likely to have been highly variable and fluctuating throughout firing, neither completely oxidizing nor completely reducing at any stage, and best described as "incompletely oxidizing." A completely reducing atmosphere during firing is difficult to achieve except under well-controlled or extreme conditions (such as complete smothering of the firing load).

Skilled potters carefully judge temperature and the end point of firing by experience on the basis of cues such as the color of the flame, the glow of the pots—red heat is visible in daylight at 550–625°C—the amount or color of the smoke emanating from the fire, or even the amount of fuel available. Once the maximum temperature is reached, it is rarely held very long, if at all; generally no more fuel is added and the temperature declines, rapidly at first and then more slowly.

Potters typically allow the vessels little time to cool after maximum temperature has been attained. Cooling may take place in an atmosphere different from that of heating if the air is allowed to circulate or if the fired pieces are covered with a layer of ash. Potters frequently lift the ash or fuel residue to allow air to reach the pots, and may even remove them from the hot coals at temperatures above 600°C (Nicklin 1981a: 356; Shepard 1976: 85). This intentional exposure to oxygen enhances color development and may, if temperatures are sufficiently high, help oxidize fireclouds. Hopi potters, however, do not remove their pots for four or more hours, after they are cool enough to be handled (Colton 1951: 74), and potters in Guinhilaran, Philippines, leave their fired vessels overnight (Scheans 1977: 20).

If black pots are desired, the firing may end with intentional reduction or smudging: the fire is smothered and the pots are covered with a dense layer of fine organic matter such as powdered manure or sawdust. This material closes off the supply of oxygen to the ware so that carbon is deposited on the surfaces and in the pores. The famous polished blackwares of Santa Clara are created by adding manure when the fire has reached its maximum heat, after which the temperature drops, and the pots are left for thirty to ninety minutes before being removed (LeFree 1975: 63–65).

10.2.2 Postfiring Treatments

Various postfiring treatments may be applied to mixed-fired pottery to improve appearance, seal surfaces to decrease permeability, and increase strength. In Papua New Guinea, for example, Azera pots may be treated by a procedure similar to docking (although it is not clear whether the paste contains calcite): river water is poured into vessels hot from the fire and stirred until it evaporates (May and Tuckson 1982: 138).

More commonly, postfiring treatments involve applying organic materials to the pot while it is still hot (table 10.2; Arnold 1985: 140). Papago potters apply a mesquite

solution to pots after firing and the vessels are reheated briefly (Fontana et al. 1962: 77–78). Tree resins are widely used, especially in Africa (see Diallo et al. 1995). Ibibio potters of Nigeria treat water pots with resin from the avocado tree to give a "superficially glaze-like appearance" (Nicklin 1981b: 177). To strengthen and beautify their vessels, the Gamo of Ethiopia treat their newly fired pots with cow dung and *etema* (Arthur 2006: 48), the liquid from the *ensete* plant in the banana family (Musaceae). In Cameroon, potters soak the pods of the acacia tree and then sprinkle the liquid on the pots after firing to strengthen them (Gosselain 1998: 101). The Shipibo-Conibo apply two resins to their pottery, one for "lending a glaze-like slip to white-slipped surfaces" and the other to waterproof the interior of vessels that will contain liquids (DeBoer and Lathrap 1979: 115). A coating of pine resin is applied by Kalinga potters in the Philippines (Foster 1956; Longacre 1981: 60; Skibo 2013: 48).

Food substances also may be applied to pots after firing and before use. In Ethiopia milk is poured into new pots and swirled around until the vessels cool (Messing 1957). Potters of Santa Apolonia, Guatemala, coat their slipped pots after firing with *agua de masa,* the liquid left after soaking corn in limewater to make tortillas; the residue left on the pots is rubbed to a high polish (Reina and Hill 1978: 63). In Papua New Guinea new pots may be sealed by boiling pawpaws, yams, or ripe cooking bananas in them, by splashing on a solution of sago flour and hot water, by rubbing their surfaces with banana leaves or passion-vine leaves, or by coating them with a milky tree resin also used to caulk boats; traditionally a new cooking pot must be covered with the blood of a pig before it can be used (May and Tuckson 1982: 49, 139, 174).

Table 10.2 Postfire Coatings and Treatments for Pottery

Substance	Location or Group
Milk	Ethiopia
Coconut milk	Philippines, Panaeati Island
Agua de masa (limewater)	Santa Apolonia, Guatemala
Manioc juice	Caribs, Brazil
Pawpaws, yams, bananas, boiled	Papua New Guinea
Sago flour and hot water	Papua New Guinea
Banana or passion-vine leaves, rubbed on	Papua New Guinea
Acacia-tree beans, boiled	West Africa
Beeswax	Sarayacu Quichua, Ecuador
Mangrove bark, boiled	Papua New Guinea
Resin, avocado tree	Ibibio, Nigeria
Resins, various	Philippines, Ethiopia, Papua New Guinea, Shipibo-Conibo (Peru), Sarayacu Quichua (Ecuador)

Source: For references, see text and Arnold 1985: 140.

10.3 Economic Realities: Costs and Losses

Initially it might seem that pottery making has the potential for being, if not lucrative, at least minimally secure. The raw materials for making pots are often obtainable at no cost, and potters may make many of their own tools, such as scrapers, paddles, anvils, bricks for kilns, and so forth. Also, in some traditional communities, and virtually all ancient ones, pottery articles were household necessities. But the utensils themselves are given low monetary (or exchange) value and the labor that goes into their creation is not adequately compensated. Two additional factors are probably responsible for much of the low economic return: the high loss rate in firing and the high cost of fuel.

Firing is the climactic step in pottery manufacture and it is a crucial one, because if it is not done properly, or if the weather does not cooperate, the vessels being fired may be lost. The loss may be only one pot or it may be several hundred, and it can represent the work of anywhere from several days to several months, depending on the frequency and volume of firing.

Cracking, the initial stage of failure or strain in a body, may originate from stresses during forming and drying, including preferred orientation, excessively rapid drying, differential shrinkage, and warping. The cracks and strains may be invisible until the vessel is fired, then they may expand as the body shrinks further or new cracks may begin to form, causing breakage or final failure of the clay body. Dunting is a particular defect that results when too rapid cooling creates stresses as the constituents of the body contract at different rates.

Table 10.3 Rates of Firing Loss with Different Kinds of Firings

Type of Firing	Place	Firing Loss	Reference
Open	Huichol, Mexico	25%, 100%[a,b]	Weigand 1969: 43
Open	Hopi, Southwestern U.S.	0–100% in firings of 4–20 pots	Colton 1951: 75
Open	Fulani, Africa	13 of 16 pots cracked	David and Hennig 1972: 24
Open	Mixco, Guatemala	10% of *comales*[b]	Reina and Hill 1978: 44
Open	Chinautla, Guatemala	5–10%	Reina 1966: 55
"Mixed"	Pakistan	<2%[b]	Rye and Evans 1976: 60
Shallow pit	Diola, Africa	11 of 179 destroyed, 8 kept for dry storage	Linares de Sapir 1969: 7
Shallow pit	Seri, Mexico	10%[b]	Bowen and Moser 1968: 115
Pit kiln	Pakistan	up to 50%	Rye and Evans 1976: 62
Pit kiln	Pakistan	25% of 400; 50% not uncommon[b]	Rye and Evans 1976: 41
Updraft	Ticul, Yucatán, Mexico	12%	Stark 1985: 174 (citing Hurd 1976)
Updraft	Tepakan, Campeche, Mexico	20%	Stark 1985: 174 (citing Hurd 1976)
Updraft	Coyotepec, Oaxaca, Mexico	20%	Van de Velde and Van de Velde 1939: 34
Slope	Philippines	18 of 148 jars	Scheans 1977: 64

Note: Rates are usually higher in the rainy season.

[a] Firing loss occasionally viewed as witchcraft or punishment. Only two observations.

[b] Figure is an estimate.

Overfiring (to too high a temperature or for too long) is a relatively infrequent defect and can lead to excessive melting and deformation, as well as to bloating and a particular type of black coring distinct from the carbon cores common in low-fired wares. Bloating results from some of the carbon in highly organic clays remaining even at extreme temperatures; the glassy melt closes the exterior pores, and because gases such as CO_2 are prevented from escaping they swell and darken the body.

A cross-cultural look at firing loss rates (table 10.3) suggests that high rates of loss are not atypical, regardless of the firing technique. Open or bonfire firings seem to be the most variable, with loss rates ranging from zero to 100% among Hopi potters

(Colton 1951: 75). The estimated loss in pit kilns averages between 25% and 50% in Pakistan (Rye and Evans 1976: 36, 41, 54, 62), and is commonly higher in the rainy season.

It might be expected from these data that large piles of wasters would be abundant at ancient production sites, but this is not always the case, because potters diligently repair or recycle their materials. Among the Diola of Senegal, cracked pots that cannot be used for holding liquids are kept for dry storage, and those damaged beyond repair are crushed for sherd temper (Linares de Sapir 1969: 7). In general, the adage "Use it up, wear it out, make it do, or do without" describes well how potters recycle their firing accidents, as detailed in this vignette on Afghan potters:

> Pieces damaged during firing are sold "as is" if not too badly deformed, or repaired with a sort of cement. The potter himself uses broken pieces to close the mouth of the kiln. In some cases he crushes sherds to add to the clay as temper. In his workshop, damaged pieces or the bottoms of jars serve as receptacles for slip and other materials. Waste clay removed during vessel manufacture is put in the bottom of a broken bowl or base of a jug, which then is used as a mold. Other fragments are used as scrapers or polishers. In general, all artisans have fragments of jars or jugs in their workshops for storing the water they use in their work. . . . During the rainy season, the garden paths are covered with sherds reduced to the size of gravel. Gardeners employ jars with broken necks as watering cans. Fragments of pottery are even used for intimate purposes.
>
> *(Rye and Evans 1976: 122–23, translated from Demont and Centlivres 1967: 57)*

10.3.1 Problems of Mixed Firing

Potters who fire in bonfires and pits, and even in ancient and modern open-topped kilns burning wood or other fuel, cannot achieve the same control of heating rate or of maximum temperature—or control over heat-related stresses within the ware—that is possible in fully enclosed kilns. Consequently, a host of problems plague mixed firing strategies: uneven firing, over- and underfiring, color blemishes, cracking, warping, and breakage. The causes, which are not mutually exclusive, include thermal shocking, contact with fuel, uneven fuel distribution, and wind.

Thermal shocking is of concern because of the rapid temperature increase and the contact of the pots with the fuel. Preheating the vessels is one way to decrease the risk. If pots are not preheated before firing, the same effect may be created by lighting the lower layer of slow-burning fuel first; most of the heat is dissipated to the atmosphere through radiation and convection, but the heat that does reach the pots effectively preheats them.

Because pottery fired in bonfires and pits has fuel placed under, around, and on top of it, vessels frequently emerge with fireclouds as a consequence of this contact. In addition, rapid temperature changes and shifts in the position of the fuel as it burns can easily crack, dent, warp, or misfire the vessels. Moreover, because of this contact with fuel, open firings are rarely used for glazed ware (cf. Reina and Hill 1978: 86, for an example from Guatemala). Although the maximum firing temperatures sometimes may be fairly high, proper glaze formation is inhibited by short or nonexistent soaking times

and generally uneven heat distribution. Moreover, the heat energy produced is not efficiently used. It has been estimated that in open cooking fires only 10% of the energy potential of wood is actually used (National Academy of Sciences 1980: 28); doubtless a comparable figure obtains for bonfire pottery firings, and this is improved only slightly by the upper ash layer insulation that accumulates during firing.

Because firing has great potential for disaster, potters select their firing times and materials with care. For example, weather conditions are a serious problem in firing pottery by the bonfire method, as a gust of wind can cause the temperature to drop as much as 246°C (500°F; Reina and Hill 1978: 24). Potters may schedule their firings for times of the day when the wind is calmest, such as in the early morning or late afternoon. Humidity and rainfall are also crucial factors. Many potters recognize that firing losses in the rainy season are generally much higher than in the dry season, and may practice their craft only in the dry season to avoid the difficulties rain causes in drying and firing their pots. Normal dampness of the soil may be compensated for by preheating the firing area to dry it or by placing a layer of sand over the ground before laying the bed of fuel.

Despite these difficulties and risks, mixed firings in the open and in shallow pits and trenches have long been satisfactory practices for non-industrial potters, and for millennia these techniques have provided a means of producing useful low-fired unglazed wares for cooking and storage. The methods are comparatively cheap and do not require the heavy capital investment needed to construct and maintain a kiln.

10.3.2 Problems of Kiln Firing

Kilns represent a substantial capital investment for potters, one that needs constant maintenance and repair. These structures must be carefully designed to make maximum use of prevailing winds, available heat, draft, and space for setting pots to ensure even heating. Even so, despite the improved firing security they provide, kilns are not without their problems. For example, strong winds can damage kiln firings: a typhoon in Japan ruined several large kiln loads (Leach 1976: 195). Also, the use of fuel is not as efficient as might be expected, because a large proportion of the energy produced is used just to heat the kiln structure itself. Small kilns have a particularly unfavorable ratio of heat distribution with respect to pots versus structure, but even in large kilns it has been estimated that 30–40% of the heat is lost (Cardew 1969: 182) through radiation, convection, and conduction.

Kilns and their components constantly expand and shrink with firing and cooling, and under these stresses they may develop cracks or flaws that can be lethal to a load of pottery. They also experience pronounced thermal gradients from top to bottom and center to sides that affect the firing of the pots. Even the rhythm of stoking the kiln during firing changes the atmosphere from oxidizing just before stoking to reducing just after fuel is added (Rye and Evans 1976: 167).

Given the risk of lost labor and fuel costs associated with misfiring, it is not surprising that large-scale pottery production centers often had specialists in setting and firing kilns. This was true in the Chinese porcelain industry, among majolica producers in sixteenth-century Seville, Spain, and in the newly tourist-oriented pottery workshops of Ticul (Yucatán), Mexico (D. Arnold 1999: 77). Experienced kiln setters and stokers understand the variables of firing and carefully load the chamber keeping them in mind.

> The firing is the climax of the potter's labour, and in a wood-fired kiln of any size it is a long and exhausting process. Weeks and months of work are at stake. Any one of a dozen things may go wrong. Wood may be damp, flues may get choked, bungs of saggars fall, shelves give way and alter the draughts, packing may have been too greedily close, or for sheer exhaustion, one may have snatched an hour's sleep, handing over control to someone else and thereby altering the rhythm of the stoking. At white heat things begin to move, to warp and to bend, the roar of combustion takes on a deeper note—the heavy domes crack and tongues of white flame dart out here and there, the four-minute stokes fill the kiln shed with bursts of dense black smoke and fire. . . . A big kiln firing has the aspect of a battlefield where men test themselves to the utmost against odds.
>
> *(Leach 1976: 195–96)*

10.3.3 Fuels and Costs

Firing loss is all the more serious because fuel is usually the highest—sometimes the only—expense incurred in pottery manufacture. Potters must balance these expenditures against the tremendous but unavoidable risk of losing the vessels and the income they represent in firing accidents. The costs (and losses) can be reduced if the potter or an assistant collects the fuel rather than purchasing it; this, however, may reduce production time and thus potential profits. (The same relationship of time/cost/profit holds for collecting versus purchasing clay; see Beals 1975: appendixes 10, 11, and 14, for data on time, labor, and cash alternatives in pottery production in Santa María Atzompa, Oaxaca, Mexico.)

Wood seems to be the preferred fuel for firing, both among modern studio potters (Cardew 1969: 171; Leach 1976: 179) and among traditional potters past and present, and it is consumed in staggering quantities. The porcelain kilns of Jingdezhen reportedly used 180 loads of firewood at 133 pounds each, and in earlier times 240 loads were burned, with 20 more consumed in the rainy months (Staehelin 1965: 38). This caused a scarcity of firewood around Jingdezhen, forcing porcelain manufacturers to travel 300 miles for wood by the eighteenth century. In the ancient Near East political and social unrest may have contributed to a shortage of fuel early in the first millennium AD, leading to reduced firing temperature of pottery at Seleucia (Matson 1971: 74). In Westerwald, Germany, the disappearance of forests plus the environmental damage caused by the emission of HCl from the salt-glazing furnaces required potters to fire with different fuels and retrofit their kilns with gas-scrubbing systems. This expensive equipment forced many potters out of the business (Lowenstein 1986: 394). Potters of the eighteenth- and nineteenth-century Staffordshire kilns used three tons of coal per ton of clay, and an experimental Romano-British kiln burned ten units of wood per unit of

clay (Peacock 1982: 25). The ratios are somewhat more favorable for firing in Pakistan, ranging between 2:1 and 3:1, and open pit kilns may actually be more efficient (in terms of fuel consumption, insulation, and air supply) than fully enclosed kilns (Rye and Evans 1976: 165).

Potters must balance complicated considerations of fuel cost and distance, as explored in a study of production decisions in Santiago ("Los Pueblos"), Mexico (Papousek 1981: 86–87, 114–15). Potters could obtain firewood from two sources. Scrap from the saw mill at El Oro was closer (25 km away) and cheaper, but because it was fresh wood it was of lower quality; a three-ton truckload supplied only enough for 5.2 firings. Furthermore, it was often not available. Wood from Ciudad Hidalgo, on the other hand, was dry, so a similar quantity supplied enough for seven firings, but Ciudad Hidalgo was 85 km distant. Table 10.4 shows the detailed costs of various arrangements of bringing firewood just for the glaze firing of vessels in 1976 (e.g., 67–129 pesos per kiln load; it does not include the costs of the first firing). Only eight years earlier, fuel for a kiln load cost 50 pesos. Although the cost of the wood from Ciudad Hidalgo was determined to be 15 pesos more per kiln load, potters preferred it because it was of better quality and there was greater assurance that it would be available.

Clearly fuel constituted an increasingly burdensome portion of the costs of producing pottery in Los Pueblos, which meant an ever narrower margin between profit and loss. Potters coped with this uncertainty by selling pots that were only partially fired or even unfired, a situation that was highly profitable to the middlemen traders. Fired but unglazed pots could be sold for 50–60% more than unfired pots; those that were glazed and second-fired sold for 100–200% more than unfired pots (Papousek 1981: 114). Regardless of the selling price, however, about one-third of the increases already had been spent on fuel and glaze.

Aside from wood, agricultural by-products are widely used for firing, particularly animal waste. Other agricultural and industrial materials include lint from a cotton factory in Bombay (Lynch 1979: 8); pruned olive branches in Spain (Curtis 1962: 496); cornstalks, sugarcane, automobile tires, and cactus in Acatlán, Mexico (Lackey 1981: 59–60); and vineyard cuttings and the sludge from pressing olives in Greece (Matson 1972: 219).

Table 10.4 Comparison of Santiago Prices of Fresh Wood from El Oro with Prices of Dry Wood from Ciudad Hidalgo, 1976 (in Pesos)

	Price per Three-Ton Truckload			Price per Kiln Load		
		In Santiago			In Santiago	
Origin of the Wood	In Place of Origin	Brought by Oneself[a]	Delivered by Others[b]	In Place of Origin	Brought by Oneself	Delivered by Others[b]
El Oro (fresh; enough for 5.2 firings)	300	350	600	58	67	115
Ciudad Hidalgo (dry; enough for 7 firings)	450	575	900	64	82	129

Source: Papousek 1981: 86.

[a] Price includes three tons of wood, plus expenses for one helper and for gas (the latter two adding 50 pesos to the cost of wood from El Oro and 125 pesos to the cost of wood from Ciudad Hidalgo).

[b] Price includes three tons of wood plus expenses for two helpers and transportation (the latter two adding 300 pesos to the cost of wood from El Oro and 450 pesos to the cost of wood from Ciudad Hidalgo).

10.4 Final Considerations

Today's ethnographic record on pottery firing might be somewhat impoverished in comparison with the archaeological record, when a full range of pyrotechnologies is considered. The problem is particularly acute in the Americas, where above-ground kiln structures are comparatively rare and much of the firing appears to have been carried out on or below the ground surface. This makes it difficult to identify such facilities archaeologically, as open firing areas and pits may have been covered (or filled, in the case of pits) with trash. Unless large quantities of obvious wasters, ash, and other indicators (Stark 1985; Stark and Garraty 2004) are recovered nearby, they are likely to go unremarked.

Another consideration is the likelihood of multiple firing technologies in use at a single time and place. Different kinds of firing strategies might have been used for different kinds of wares, varying according to categories of consumers (elite vs. commoner), pastes (coarse vs. fine), and demand intensity (see Miller 1997; Pool 1997). Firing in pits, because of their relative ease of closure, seems especially suited to efficient production of gray or black wares in incompletely oxidizing or reducing atmospheres.

Finally, a recent study compared data on firing from 80 traditional settings, three in Mesoamerica, four in the United States, and the remainder mostly in Africa and also Asia (Smith 2001). These were compared with regard to fuel ("heavy" vs. "light"), facilities (bonfire, depression, kiln), scale (1–600 pots), schedule (time), and temperature. Perhaps because so many variables were considered simultaneously, few correlations were noted and most data values overlapped (e.g., among facilities, fuels, duration of firing). One correlation that appeared to be positive was between rate of heating and type of firing facility: firing in bonfires and "depressions" was associated with rates below 20°C per minute whereas various kinds of structures had heating rates between 20°C and 40°C per minute (Smith 2001: 997). None of the firings in "closed or insulated structures" in this sample had heating rates above that rate.

11 Exchange and Household Provisioning

> Ethnoarchaeological research has shown that dogs and children account for many broken pots.
>
> Skibo 2013: 17

From the viewpoint of artifacts having cultural biographies, after a clay vessel has been fired or "born" the next stages in its life cycle are filled with interactions with humans through active roles in household affairs, ritual, or in other settings. This active stage in systemic context (Schiffer 1972, 1976) begins with acquisition ("adoption") by consumers, if other than the pottery-producing unit, proceeds through various uses, recycling, and replacement, and ends with discard and entry into the archaeological record. Questions about artifact movements between systemic and archeological context —how artifacts spent their use-lives—lie at the heart of archaeological field work and the study of the recovered pottery. This chapter addresses the first stages of that process: pottery's movement to consumers and membership in household assemblages.

11.1 Distribution: From Producer to Consumer

Pottery making may be a small-scale endeavor for "own-use" within the potter's household. Among the Fulani, for example, pottery stays in the same quarter of the village in which it was manufactured and "rarely travels more than 200 meters between producer and consumer" (David and Hennig 1972: 21). Among the Shipibo-Conibo a census of twenty-five households revealed that only 4% of 325 vessels were manufactured outside that household (DeBoer 1984: 354).

At the opposite end of the production scale, pottery-making may be a sizeable mass-production enterprise directed toward a body of anonymous and often distant consumers. For anything other than own-use, the process(es) by which pottery reaches its users is a matter of considerable interest, as the activity informs on broader social and economic institutions of a society, including what is commonly referred to as the political economy (see Hirth 1996).

Distributional processes likely represent the most severe disjunctions between the ethnographic present and the archaeological past. Disjunctions result from the penetration of cash economies, industrial capitalism, and globalization (collectively part of the modern world system; Wallerstein 1974), along with tourism, motorized travel and transport, and cheap plastics. These complex factors have contributed to sharp declines in manufacture and use of traditional pottery containers over the past century, and to transformations in the kinds of items potters produce (e.g., small tourist items or "airport art"; sec. 26.2.1) and the ways these goods reach consumers. Thus appropriate direct modern analogies for the movements of goods and producer-consumer interactions in ancient times are scarce, particularly since the last quarter of the twentieth century.

11.1.1 Reciprocity, Redistribution, Exchange, Trade

Circulation of goods in non-industrialized economies was often described in terms of three processes—reciprocity, redistribution, and exchange (table 11.1; Polanyi 1944, 1957; see also Earle 1977; Hodder 1978: 199–211; Sahlins 1972). These processes are generally considered idealizations, stand-alone categorizations of evolutionary schemes of complexity similar to—and often part of—social and political typologies such as band, tribe, chiefdom, etc. The term trade is sometimes considered synonymous with exchange, but has different institutional implications. More recent discussions of household (or domestic) economies (e.g., Hirth 2010) and, especially, political economies of complex societies (e.g., Feinman and Nicholas 2004; Hirth 1996; Smith 2004) have highlighted the multidimensionality of all these conceptual formulations.

Reciprocity refers primarily to movement of goods between individuals based on more or less symmetrical relationships. The objects moved are typically considered "gifts" (Mauss 2000), but rather than being voluntary and spontaneous, they are part of

"obligatory, premeditated, and carefully calculated" interactions (Wallis 2011: 13). Reciprocity has been categorized with reference to the social distance between the participants as generalized (e.g., hospitality, care of the elderly), balanced (socially mandated gift exchanges, feasting, bride-price, etc.), or negative (taking place between relatively distant partners and perhaps involving haggling) (Sahlins 1972). Material transactions are significant in these interactions, but the social and symbolic aspects are more so. Reciprocity is not limited to "simple" or "primitive" societies, as evidenced in Western social expectations surrounding dinner parties and holiday gift-giving.

Redistribution has two critical components: resource mobilization, or pooling of surplus goods, and centrality. In its idealized form, redistribution takes place in relatively formalized relationships in which goods are accumulated or appropriated, moved to a center, and then reallocated or dispersed (see Hirth 1996: 221–24). In practice, much redistribution may take place voluntarily and absent any centralized (elite) direction or location, either within or between production locales, and it may range from family activities to community feasting—including reciprocity—to regional fairs.

Table 11.1 Idealized Categories of Circulation of Goods

- I. Based on Personal/Social Relationships
  - A. Reciprocity
    - Generalized
    - Balanced
    - Negative
  - B. Redistribution
    - Leveling mechanisms
    - Domestic pooling and sharing
    - Share-out
    - Mobilization/appropriation
- II. Based on Impersonal Factors
  - A. Exchange
    - Market exchange
    - Middlemen
    - Market places
    - Daily or periodic
    - Fixed or rotating
    - Local or regional
    - Administered or supply/demand
  - B. Trade (distance)
    - Interregional interaction
    - World-systems

One analysis identified four types of redistributional institutions (Earle 1977: 215–16), including leveling mechanisms (e.g., North American Northwestern coastal potlatching), domestic household pooling and sharing, and share-out (allocation on the basis of cooperative effort such as hunting). These are common throughout the range of societal complexity, and tricky to identify archaeologically. The fourth redistributional strategy is mobilization, or appropriation of goods and services by and for a separate entity, usually an elite. The goods mobilized may be ordinary foodstuffs or prestige items (Hirth 1996: 216–17). Such mobilization is characteristic of appropriative political economies, in which "political power initiates the hierarchical transfer of goods and services" (McAnany 2004: 146), and exists only in hierarchical (ranked or stratified) societies. In archaeological studies, appropriative economies have been associated with various kinds of labor control or "financing"—state-controlled (or centralized) production, as through tribute or corvée labor—to underwrite civic-ceremonial enterprises.

Exchange may refer in a general sense to any transactional process—including dyadic reciprocity/gift-giving and redistribution—in which goods change hands in return for some other good, service, or intangible. More narrowly, the term exchange may be used specifically for impersonal market or commercial exchange, which is governed by considerations other than social relations among individuals. Goods that are produced specifically for exchange are called commodities (see sec. 22.2). Typically mass-

produced in the industrial world, commodities are "alienable" goods: that is, ownership is easily transferred (through exchange). Such goods lack the heavy symbolic value, at least partially conferred by social memory and history, that permanently binds "inalienable possessions" to their creators/owners: even if given away, such objects still belong to their owners, individual or corporate (Mauss 2000; Mills 2004; Weiner 1992).

Trade is sometimes a collective rubric incorporating the activities of reciprocity, redistribution, and exchange. Trade may be distinguished from exchange, however, with the former referring to the material goods being moved—the "economic" or commercial, sensu stricto—in a market economy and the latter emphasizing the underlying social-interactional processes (for a review, see Oka and Kusimba 2008). In general, trade refers to appropriational processes involving significant distance and transport (interregional trade; interregional interaction) and in which there is often some relatively formal, institutional, and permanent relationship between partners as individuals or official agents. World-systems theory (Wallerstein 1974), developed to describe the complex linkages of colonialist-capitalist economic interactions beginning in the sixteenth century, has also been applied to precapitalist systems.

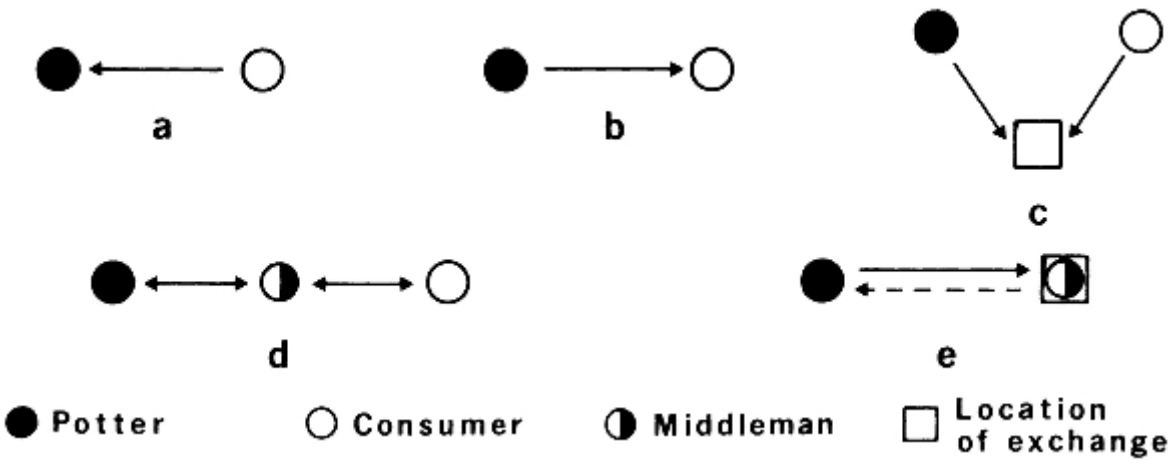

Figure 11.1 Model of pottery distribution relationships: *a*, consumer travels to potter; *b*, potter travels to consumer; *c*, both potter and consumer travel to a third location; *d*, pottery is exchanged through a middleman; *e*, potter takes goods to a central redistributive agency.

In the case of pottery, vessels may change hands through gift-giving or other processes of reciprocal social obligations, through redistributive mechanisms, or as part of more impersonal exchange and trade (fig. 11.1). Sometimes the interactions are direct: potters bring their pots to consumers, consumers go directly to potters, or both, as in Dalupa, Philippines (fig. 11.1*a*,*b*; Stark 1991: 68). In the former, potters might act as itinerant vendors (fig. 11.2), for example in Papaguería (Fontana et al. 1962: 23), the Amphlett Islands (Lauer 1970, 1971), and the Nicoya peninsula of Costa Rica (Stone 1950). In some caste-based societies, potters work through patron-client relationships

(e.g., Arthur 2006), which can involve production on consignment or commission (Howry 1976; Scheans 1977: 46).

Figure 11.2 A rural Muslim potter and his wife travel with a bullock cart loaded with pots for sale in western Rajasthan, India. They sell along the road, but primarily in small villages and towns where few pottery shops are found. Photograph by Carol Kramer.

Pots may move to consumers through a third party or parties—a wholesaler or middleman who interacts with potters, consumers, or both (fig. 11.1*d*). Occasionally a middleman acts as a monopolist in buying from potters and extending credit to them, as in the case of don Asunción in Mexico (Papousek 1981: 79–82, 100–105). Or, pottery may change hands at a third, separate location (fig. 11.1*c*), such as a marketplace or fair or, less formally, a convenient and busy street corner or other area. The origins of formal market arrangements are poorly understood and beyond the present scope.

The ethnographic record indicates that market*places* are highly variable in timing and location. Marketplaces may be permanent (daily) or periodic, operating within a weekly or monthly schedule, or associated with fairs based on religious scheduling. They may be in fixed locations or rotating (usually also periodic): local, in the vicinity of the potting community, or regional, sited some distance from the producers. Marketplaces may be administered or based on supply-and-demand price mechanisms, the latter typically associated with capitalism. At these locales, potters or members of potting families may interact directly with local consumers or with merchants who carry the pottery farther away in secondary distribution.

11.1.2 Costs and Prices

Pots have use-value and some degree of exchange value, regardless of whether they can technically be called commodities. Some exchange may involve bartering pottery or swapping it for other goods, often food. The Papago in the American Southwest traded pottery for flour, salt, sugar, coffee, beans, or corn as well as cash (Fontana et al. 1962: 22–23). Similarly, at Begho, Ghana, West Africa, "plantains, cocoyam, palm nuts and dried cassava . . . are made available at [the potters'] doorsteps; cowries and gold dust were also used in exchange before modern currency" (Crossland and Posnansky 1978: 87). This system is not restricted to the irregular changing of hands of pottery produced in-home: workshop potters of Vounaria, Greece, exchanged their wares for wheat (Matson 1972: 220; see also Miller 1981: 224). Similarly, fifteenth-century majolica potters in Valencia, Spain, were paid in money or in grain, textiles, horses, or ingredients for their ceramic glazes (Van de Put 1911: 14).

The inflationary economy of the middle twentieth century placed a premium on flexible (and rational-actor–based) selling strategies, as documented among full-time potters in the Philippines:

> Most of the San Nicholas potters prefer to retail their wares whenever possible in order to maximize their gains in a market that they know is subject to rapid fluctuations of supply and demand. Indeed, some will even take their wares to hawk in distant towns in order to receive the highest price. Others will barter their stock for whatever their family might need. Rice, of course, is a preferred item in bartering. Because of this they try to barter for it before the time of harvest since rice prices are the highest then and bartering is based on the volume capacity of the item to be traded. If they cannot do that they will advance the pots and be paid at harvest time an agreed amount plus interest.
>
> *(Scheans 1977: 103)*

The actual forms of the exchange and the value of the goods are highly variable in most of these kinds of transactions. Where consumers travel to the potters, the prices of pots are relatively stable (Hodder 1979a: 17), without the inflationary effect of distance. In many situations of household production and sales, the stability of prices may be a consequence of informal price fixing or social sanctions against competitive pricing and underselling, as among the potters of Santa Clara, New Mexico (LeFree 1975: 68) and Matti, Philippines (Scheans 1977: 46).

However, unlike the general picture of potters abandoning their enterprise as consumers abandon clay cooking utensils, in some places pottery making is flourishing. This is largely because the sale of pots has become an important source of cash income and otherwise-unobtainable financial freedom, particularly for women (Fontana et al. 1962; Stone 1950). Among the Kisi in southwestern Tanzania, for example, the introduction of a cash economy led to the decline of the traditional fishing-based livelihood and increased the importance of pottery making because it brings in cash (Mijango 2001). Pottery is still made by women, who have been empowered by the changes because of the importance of cash for beginning married life. In Walangama, Sri Lanka, pottery making flourished in the late twentieth century, with potters supplying the

makers of water buffalo–milk yogurt with small pots that were used only once (Winslow 1996, 2002). The need for continuous replenishment of these dishes, plus the presence of modern potters' wheels, ready supplies of clay and fuel, and a potters' cooperative organization, led to the town's marked prosperity.

Although distance and supply are probably most influential in determining the cost of vessels, other mechanisms operate as well, though not always consistently. A slip, glaze, or decoration may confer additional value to a pot (e.g., see Hardin 1977: 115), because of labor and materials. Among the potters of Los Pueblos the presence of a glaze is a major determinant of the cost of pots to merchants (Papousek 1981: 84, 114–15). At Begho, however, the presence or absence of a slip does not influence the cost of a pot (Crossland and Posnansky 1978: 88). In areas of strongly seasonal climate, weather factors may also influence supply and hence price; this is seen with respect to barter arrangements.

Quality plays a role, too. Women heads of households among the Gamo prefer the pots of certain villages because of their strength and long use-life (Arthur 2006: 57, 59–60). In Nigeria, Ibibio consumers acknowledge that Igbo pots are better than their own and last longer in use, and they are therefore willing to pay as much as 50% more for them (Nicklin 1981b: 183). Potters often claim that minor variations of rim form and decoration are efforts to cater to customers' preferences (Birmingham 1975: 382). Among small-scale producers, potters may gear their output to the preferences of specific consuming groups to maintain a market (Crossland and Posnansky 1978: 88). Unfortunately, little has been done with the "artifact-acquisition perspective" (Walker and Schiffer 2006) as it pertains to pottery consumers.

11.1.3 Cautions in Interpretation

These systems of interaction—the reciprocity, redistribution, exchange, trade, and market models—are heuristics, or idealized categories of behavior. As in many applications of behavioral constructs to actual situations, particularly in analogical reasoning from ethnography to archaeology, several cautions may be registered.

First, any combination of these arrangements may co-occur in a single society. Similarly, different exchange relations and mechanisms may result in similar patterns of artifact dispositions in a region (see Earle 2002: 95–96). Thus no single behavioral category can describe an entire economy in the present, and likely in the past, because of the simultaneous existence of multiple distributive arrangements. For example, in the Baringo district of Kenya either potter or consumer may travel to the other (Hodder 1979a: 11–12). In Papagueria, Arizona, there was a gradual change from potters' acting as traveling vendors to their selling their pots from their homes (Fontana et al. 1962: 22–24). Walangama women potters used to carry their pots to consumers but demand has increased to such an extent that they now sell to middlemen with trucks (Winslow 1996, 2002).

Second, exchange networks, whether local or long distance, are important not only in supplying necessary goods and building economic contacts, but also in maintaining information flow and social relations (see DeBoer and Lathrap 1979: 115–16; Spriggs and Miller 1979: 28), including political and kinship alliances and even enmities. Among the Yanomamö of Venezuela the Momariboweiteri claimed they neither knew how to make pots nor had suitable clays. They obtained their pots from a group they were allied with, trading them on to a third allied group, the Kaobawa. When the alliance with the potting group faltered, the Momariboweiteri suddenly "remembered" how to make pots and "discovered" suitable clays nearby and so maintained their alliance with the Kaobawa (Nicklin 1979: 450, citing Chagnon 1968: 100–101). Related to this alliance maintenance, it should be noted that boundaries between social or cultural (ethnic, political, tribal) categories or environmental zones may not hinder exchange (Hodder 1977: 269; Reina and Hill 1978: 216). Material exchanges will also vary between centralized and noncentralized societies (Hodder 1978: 211–34).

Third, entrepreneurs—businesspersons who undertake new initiatives, often with considerable risk—or a centralized authority may be significant in these processes. Pottery production today is heavily influenced by commoditization and monetization, as well as industrial capitalism and its products. Entrepreneurs and middlemen play important roles in commodity production, marketing, and pricing. This is particularly evident in the status of powerful individuals who have accumulated sufficient wealth to own trucks, thereby dominating distribution and, by extension, production as well (Papousek 1981; Winslow 1996, 2002). Obviously trucking could not have played a part in antiquity, but other kinds of entrepreneurial traders could have figured significantly, especially in large, complex societies. The role of an institutionalized merchant class, such as the *pochteca* of Aztec Mexico, or other long-distance traders may be analogous to that of truckers, both by virtue of controlling distribution and by their access to powerful knowledge about a broader world and its affairs (e.g., Helms 1988).

Until the advent of today's motorized transport, pottery moved overland to consumers by pack animal, wheeled carts (fig. 11.2), or, in areas lacking the wheel such as the Americas, human carriers. Even today, travel by foot may still be the most effective marketing scheme where road systems are poorly developed. In mid-century Ghana, for example, it was estimated that only 2% of an annual production of 90,000 vessels was transported by road (Crossland and Posnansky 1978: 87). In highland Guatemala, two types of middle traders were known: *regatones*, male or female, operated permanent stalls in regional (rather than local) markets (fig. 11.3); *comerciantes* were itinerant merchants who traveled throughout a relatively broad area, either on foot or with motorized transport, and sold to individuals or *regatones* at more distant markets (Reina and Hill 1978: 207, 215). As George Foster (1965: 56) notes, high-quality pottery may travel 150 miles in primary distribution and then even farther in secondary distribution. The attractive lightweight *tinajas* produced in Chinautla and nearby

communities outside Guatemala City were sold in the Flores area market, approximately 400 km north (ground travel), as late as the early 1970s. Flores was not accessible by land vehicle from the Guatemala highlands until 1970, so these jars had to be transported by human labor or pack animal. The pottery-making Kalinga village of Dalupa, on a steep hill, is still inaccessible by vehicle (Beck 2006b: 31).

Figure 11.3 A pottery stall in the main bus terminal market in Guatemala City in 1974, where pottery vessels from all over the highlands could be found (see also fig. 26.2). This stall sold varied glazed and unglazed cooking wares (basins, flat griddles or *comales*, drinking mugs) as well as the more elaborate tourist-oriented white-slipped "urban ware" visible to the woman's left: vases, *angelitos*, candelabra. The glazed and unglazed vessels with faces are braziers.

11.2 Consumers: Ceramic Censuses and Household Assemblages

Two questions that have long preoccupied archaeologists in studying the formation of the archaeological record concern the numbers of whole pots represented by the thousands of sherds recovered at a site, and the time spans that the vessels were in use. These materials from individual residential structures are the remnants of what was a household or domestic ceramic assemblage in systemic context. Unfortunately, it is rare to encounter domestic structures with complete assemblages retained on their floors as a result of sudden Pompeii-like abandonment, and so these questions have to be approached indirectly, or by analogy.

Ceramic ethnoarchaeological studies have provided insights into domestic ceramic assemblages through inventories or censuses of whole vessels in households in pottery-making and pottery-using communities. These studies have also documented patterns and rates of pottery reuse/recycling, replacement, and discard or passage into the archaeological context. Inventories give details on the numbers of pots in individual households and their uses, both in terms of general functions such as cooking, storing, and carrying, as well as more specific activities. For example, cooking may involve boiling, frying, baking, or toasting many different kinds of foods, liquid and solid, all of which may be done in different shapes and sizes of pottery vessels. Censuses also give information on the use-lives or longevity of the tallied vessels.

Observed or elicited information in these tallies ideally includes the native name for the vessel, its dimensions (including volume), use(s), age (date of manufacture), maker or origin, decoration (if any), frequency and location of use, location of storage, and anything significant or unusual about it. Also useful is a count of nonpottery containers (metal, factory-made china, plastic, wood, or basketry) in use in the households as alternatives or replacements for traditional clay pots (see Deal 1983: 140–43). With the florescence of ethnoarchaeological research in the late twentieth century, many inventories are available, and they also register the accelerating impact of plastic and metal utensils in kitchenware.

11.2.1 How Many Pots?

Much of the above information is missing from early ethnographic accounts, and the most commonly provided observation is simply a count of the number of vessels in a household. Table 11.2 presents data from ceramic inventories taken before 1985, which reveal a broad range in number of pots per household and in the composition of household vessel assemblages. Of the 12,518 vessels tabulated in 291 households in 10 communities, most (4758, or 38.0%) were used in cooking, while much smaller numbers (435, or 3.5%) were used for storage. The percentage of the individual assemblages that constituted cooking vessels ranged from 25.9% (Shipibo) to 87% (Dangtalan, Kalinga), while the range of storage vessels was from 2% (San Mateo

Ixtatán) to 30.8% (Conibo). Households in Chanal and Aguacatenango, Mexico, did not use any pottery vessels specifically for storage, instead having containers of perishable materials, plastic, or metal (Deal 1983: 165, 166).

Table 11.2 Some Ethnographic Pottery Censuses

	Cameroon				Philippines				Peru			
	Fulani[a]		Gisiga[a]		Dangtalan[b]		Dalupa[b]		Conibo[c]		Shipibo[d]	
Vessel Type	***N***	**Years**[l]	***N***	**Years**[m]	***N***[n]	**Years**	***N***[o]	**Years**	***N***	**Years**	***N***[p]	**Years**
Cooking pots												
General												
Large					268	13.0–13.8	33	3.5–5.4	10	1.0	18	
Small/medium	180	2.6	20		303	4.2–4.6	255	9.0	30	.8–1.5	25	
Storage	81[r]	10–13	26[s]		52	8.2	87	7.2	37	1.0–2.2	48	
Bowls	33	2.7	8						30	.47	45	
Other serving									8[w]	.25	23[x]	
Other	19	4.2	3		33		14		5		7	
Total pots	313		57		656		389		120		166	
Mean per house	20.9		9.5		13.4		8.8		17.1		15.1	
Median age		5.4								.96		
N households	15		6		49		44		7		11	
N potters	7		2						9		13	

	Guatemala				Mexico									
	San Mateo I[e]		Zunil[f]		Tarahumara[g]		Huichol[h]		Metepec[i]		Chanal[j]		Aguacatenango[k]	
Vessel Type	***N***[q]	**Years**	***N***	**Years**	***N***	**Years**	***N***	**Years**	***N***	**Years**	***N***	**Years**	***N***	**Years**
Cooking pots														
General	22.6 (2–50)		6		3	1–2	8		89		1885		2435	
Large			1				11							
Small/medium			4				15							
Storage	3.7		1		1	3–5	2		70[t]		343[u]		389[v]	
Bowls			3						33					
Other serving			2				13		90[y]		269		505	

Other	30.4	2		13	24	836	937
Total pots	2907	19[z]		62	306	3333	4266
Mean per house	57		7–8[aa]	12	51	62.9	85.3
Median age							
N households	51	1	10	5[bb]	6	53	50
N potters							

[a] David and Hennig 1972: table 3.

[b] Longacre 1985: tables 1–3.

[c] DeBoer 1974: 338.

[d] DeBoer and Lathrap 1979: 122–23.

[e] Nelson 1981: 115.

[f] Reina and Hill 1978: 246–47.

[g] Pastron 1974: 108–9.

[h] Weigand 1969: 29.

[i] Kirkpatrick 1978: 49.

[j] Deal 1983: table 1.

[k] Deal 1983: table 1.

[l] Median.

[m] Ages not given because of recent arrival of Gisiga in village.

[n] 1979–80.

[o] 1981.

[p] Excludes those made for sale.

[q] Mean.

[r] 34 vessels called "cooking-storage vessels."

[s] 12 vessels called "cooking-storage vessels."

[t] 70 ollas are called cooking and storage vessels.

[u] No storage vessels noted, but water jars are tabulated here as storage.

[v] No storage vessels, but water jars tabulated here as storage.

[w] Beer mugs.

[x] Beer mugs.

[y] Variety of beverage mugs and pitchers.

[z] All vessels newly purchased for setting up a new household.

[aa] Range is up to 19.

[bb] *Ranchos*—extended family residences with 4–42 members.

Table 11.3 Proportions of Vessels in Ethnographic Censuses Used in Various Activities

Census Location	Cooking	Storage	Serving	Number of Pots[a]	Number of Households
Fulani	57% (150)	25.9% (81)[b]	10.5% (33)	313	15
Dangtalan	87% (571)	7.9% (52)		656	49
Dalupa	74% (288)	22.3% (87)		389	44
Conibo	33.3% (40)	30.8% (37)	31.6% (38)	120	7
Shipibo	25.9% (43)	28.9% (48)	40.9% (68)	166	11
San Mateo Ixtatán	56% (1,628)	2% (58)		2,907	51
Huichol	54.8% (34)	3.2% (2)	21.0% (13)	62	5
Metepec	29.1% (89)	22.9% (70)[b]	40.2% (123)	306	6
Chanal	56.5% (1,885)	10.3% (343)[c]	8.0% (269)	3,333	53
Aguacatenango	57.1% (2,435)	9.1% (389)[c]	11.8% (505)	4,266	50

Sources: See table 11.2.

[a] Total number of pots counted; excludes those given as "other" in table 11.2.

[b] Some vessels were originally given combined cooking and storage functions; these are all tabulated here as storage.

[c] No storage vessels were specifically noted, but water jars were tabulated here as storage vessels.

Serving vessels were relatively rare in these assemblages (table 11.3), accounting for 544 vessels (4.3% of the total), while 3841 (30.7%) functioned in "other" activities. With respect to the serving vessels, the data for three communities (San Mateo Ixtatán, Dalupa, and Dangtalan) lacked tabulations for this functional category; for the remaining seven communities, percentages ranged from 8.1% (Chanal) to 40.9% (Shipibo; see also Metepec).

The high frequency of serving vessels among the Shipibo can be explained by hospitality customs, which dictated that guests should be served from new, unused beer mugs (DeBoer and Lathrap 1979: 124). Traditional beverages used in ritual or as part of regular domestic consumption—various kinds of beers or mead-like drinks in the Andes (e.g., Jennings and Bowser 2009), Mesoamerica (Litzinger 1983), and Africa (Arthur 2003; Fowler 2006); wine in the Mediterranean region—are likely to have played a greater role in shaping the content of pottery assemblages than commonly thought. It is customary to think of such drinking in terms of lavish feasting (Dietler and Hayden 2001), Roman bacchanals, and Greek *symposia* (drinking parties) along with the cups, beakers, chalices, *kylixes*, and kraters used in service. But in many places

beer is considered a food and is consumed as such as part of daily domestic and social life. Among the Zulu, traditional sorghum beer was associated with the ancestors, and for that reason there was little change in pottery serving and drinking vessels for beer since the nineteenth century. A new type of beer made with commercial ingredients began to be produced in the nineteenth century, however, and aluminum pots ("white people's pots") were permitted in its brewing, because it was a type of beer "foreign to the ancestors" (Fowler 2006: 100–101).

The wide range of vessel types, sizes, and numbers indicates that multiple factors influence the size of the *batterie de cuisine* in pottery-using households, and these have been the subject of numerous ethnoarchaeological studies. One seemingly obvious variable in predicting household inventory size is the number of co-residents, but this is not a direct linear relationship. What may be equally or more meaningful is age-grade composition (number of children versus adults), as each generation has different eating habits and nutritional requirements, necessitating different kinds of pots (see Nelson 1981: 109–12, also 1991). Related variables include social composition of the food-consuming group, the number of meals cooked per day, and other factors relating to contexts of vessel use.

There may be a trade-off between numbers and sizes (capacities) of vessels (Tani 1994: 56). In Wanka households in highland central Peru, a typical kitchen assemblage consists of four or five ollas, two larger ollas, one *chata* (a squat olla used for frying), and one *tostadera*, an open form for roasting corn (Hildebrand and Hagstrum 1999: 34). An increase in household membership may be accommodated by either more vessels or larger vessels.

Another salient concern is the socioeconomic status of the household as measured by, for example, land owned or farmed, participation in religious/political office, other activities such as dairying, or possession of modern cash goods and conveniences. This relates to household foodways—the kinds and varieties of foods consumed and the techniques employed in preparing and consuming them. All these considerations influence the number of kinds of pottery vessels and the absolute numbers of vessels in a household, and also the ability to acquire nonlocal vessels or modern substitutes of metal or plastic (David and Hennig 1972: 17; Deal 1983: 148–53; Longacre 1985: 337; Miller 1985: 74; cf. DeBoer and Lathrap 1979: 124).

There may be some redundancy of vessel forms or multifunctionality of individual vessels within an assemblage. That is, common or primary vessel forms are often sufficiently nonspecialized in size and shape (and probably also technological characteristics) that each could serve reasonably well in various activities. They represent adaptation through generalization rather than through specialization: a strategy for satisfying multiple needs adequately rather than a single function optimally. For example, a single vessel may function for processing, cooking, and serving, and another may be used for carrying, processing, and storage, rather than there being a separate vessel form for each activity.

Many vessels, for example, in Bé, Cameroon, and Metepec, Mexico, are described as being "cooking/storage" vessels. They are tabulated here in the storage category, but this dual usage is probably common and is important for archaeologists seeking to ascribe functions to archaeological pots. Similarly, in Chanal and Aguacatenango, Mexico, vessels were not specifically identified as storage vessels, but while the vessels were themselves being stored they often held a variety of foods, dry goods, and other supplies (Deal 1983: 167).

An additional problem concerns the context of these ethnographic observations: they come from pottery-making communities in the late twentieth century. One might well ask to what extent they are comparable with non–pottery-making villages, where pottery may be less available and more costly. A related question is whether these assemblage data are valid for pre-industrial times before the advent of plastics and metal containers: it was estimated that the Fulani, for example, may have had twice as many clay pots in precolonial times as they do now (David and Hennig 1972: 21). Might there have been more functionally specialized vessels too? Significantly, it is serving and storage vessels that occur in low frequencies in these inventoried households. Modern substitutes are adopted more readily for these functional categories than for cooking, where traditional diets and taste preferences continue to favor traditional clay vessels.

On the one hand, therefore, it might be appropriate to view the ethnographic domestic assemblage data as a baseline or minimum-number-of-pottery-vessels estimate. On the other, it is possible that before plastics were available a larger proportion of household containers were made of perishable wood, basketry, or leather rather than pottery. Distortions in the relative numbers of pottery versus other kinds of containers are difficult to retrodict.

11.2.2 Pottery Use-Life

Questions about the longevity of the pottery recovered at a site have been investigated through ethnographic and ethnoarchaeological efforts to assess a vessel's use-life, or how long it is used before being damaged, recycled into another function in systemic context, and discarded. Various methods have been used for this purpose besides the inventory procedure: interviews in Mesoamerica (e.g., Deal 1998; Foster 1960; Nelson 1991), South America (DeBoer 1974), and Africa (David 1972; David and Hennig 1972) and data on breakage among the Kalinga (Tani 1994). These early estimates of the longevity of cooking pots ranged anywhere between three months to one year up to two to ten years (David and Hennig 1972: 19; DeBoer 1974: 341; Foster 1960: 608; Irwin 1977: 291, cited in Longacre 1985: 336; Longacre 1985: 339).

Foster's estimate was based on kiln-fired, glazed pottery produced at Tzintzuntzan, Mexico, and he suggested that low-fired, unglazed pottery may have a shorter use-life of only six months (Foster 1960: 608). The data from other communities for which unglazed ware use-life is available do not bear out this supposition, however. A

longitudinal study of pottery assemblages in two communities in the Philippines revealed that over a four- to five-year period more than one-third of the original total of 720 vessels survived; 291 pots (40.4%) were broken, and 137 (19%) were sold, bartered, or given away (Longacre 1985: 339–40).

These data reveal a tremendous disparity in pottery use-life from area to area, and the notion of an "average life span" for pottery is misleading. Nonetheless a combination of observations—consideration of the recovered pottery's use-related properties along with information on use-life, frequency of use, replacement rates, and discard rates—provides opportunities to assess the issue (see DeBoer 1985; Mills 1989). In addition, a longitudinal comparison of use-life estimates of Kalinga pots revealed a systematic bias in the inventory method used in early studies in which broken vessels were not properly taken into account (Tani and Longacre 1999). Recalculation of the use-lives of 862 "regular" cooking pots yielded an estimate of 2.2 years.

Many factors affect breakage rates and hence use-life of utilitarian pottery (Foster 1960: 608; Arthur 2006: table 6.1). Some may be consequences of flaws in the manufacturing process, such as poor tempering choices, incomplete wedging, too rapid drying, or improper firing. Additional technological concerns relate to the strength of the ware and other physical, mechanical, and thermal properties, such as the repeated cycling of a cooking pot in and out of heat. Gamo pots frequently crack at the base because of these stresses (Arthur 2006: 102). In Mesoamerica, the microstructural requirements of thermal stress resistance and the flat, plate-like shape of traditional tortilla griddles (*comales*) make them extremely fragile (see Weigand 1969: 24–25).

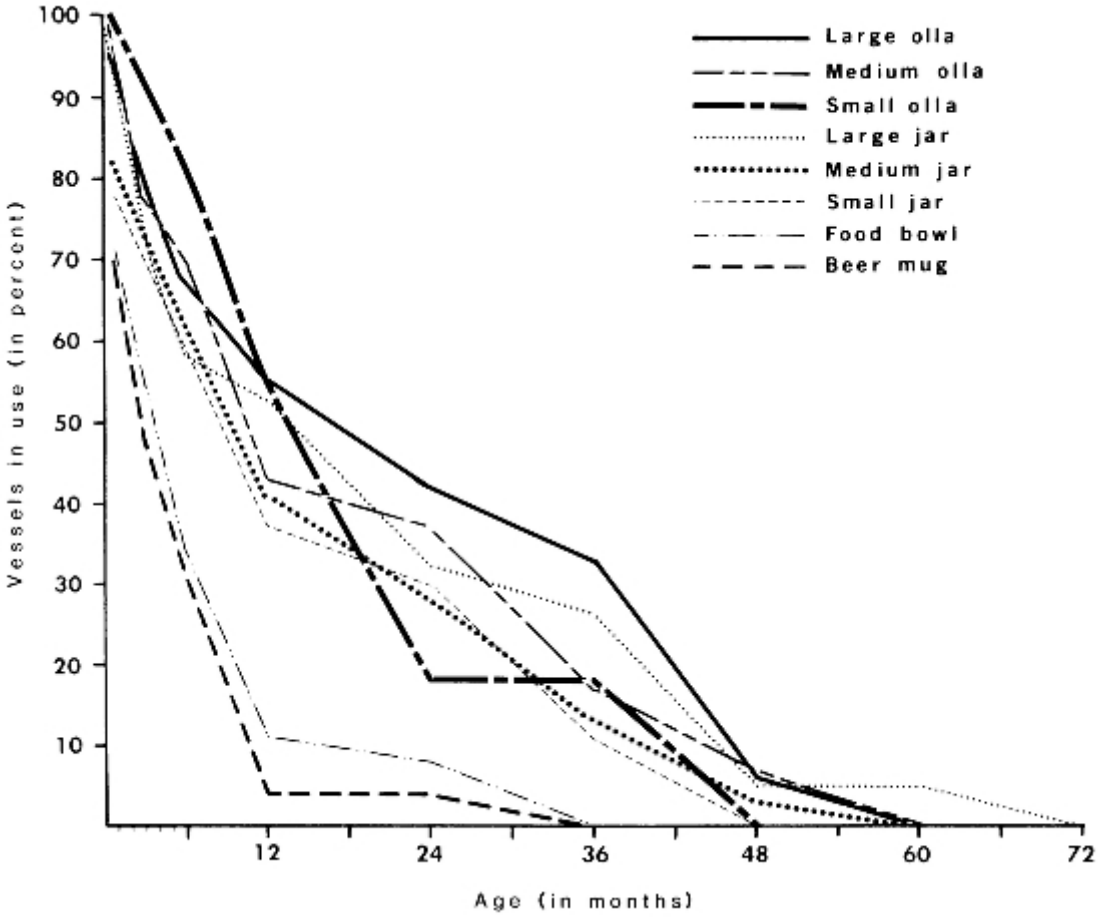

Figure 11.4 "Survivorship curves" for eight major Shipibo-Conibo (Peru) vessel forms. Note long use-life of large jars and large ollas and very short use-life of small serving vessels such as food bowls and beer mugs. After DeBoer and Lathrap 1979: fig. 4.5.

The size and weight of the vessel are important determinants of longevity cross-culturally (Shott 1996), and are closely related to frequency of use (fig. 11.4; see Deal 1983: 155–56; DeBoer 1985; Graves 1985: 23). Small or medium-sized, easily portable pots such as water-carrying jars or serving/eating vessels are likely to be broken relatively quickly because they are used and moved frequently, perhaps several times a day. In northern Peru, the ollas used for brewing *chicha* (maize beer) last only two months if used once a week, and a mixture of clay and dung is smeared on the outside of the pots to make them last longer (Bankes 1985: 275–76). Large, heavy vessels that are rarely if ever moved, such as water-storage jars set into the floor or ceremonial cooking pots, have a longer life span. In Mexico, a "fiesta pot" in Tzintzuntzan was about 40–50 years old (Foster 1960: 607) and a large Huichol cooking olla may have been 70 years old (Weigand 1969: 33). Pots for importing honey at Bé, Cameroon, were more than 30 years old (David and Hennig 1972: 13).

The proximity of vessels to activity areas or to the movement of children or domestic animals such as dogs, pigs, and chickens is a frequent cause of damage, especially if the pots are used on or near the floor rather than on tables (see Longacre 1981: 63–64;

Weigand 1969: 24). Other considerations include practices in caring for vessels, including cleaning, storage, and repair. In addition, the cost of pottery is important (Foster 1960: 608): where pottery is inexpensive and easily obtained, carelessness in its use may be the norm. The costs of pots generally relate most closely to weight and size, as large, heavy vessels require more time, skill, and raw material in manufacture.

11.2.3 Recycling and Replacement

The major concern in manufacturing a fired ceramic is to achieve a product suitable for its intended purpose, be it aesthetic or functional. Suitability and success in this endeavor depend on both the materials used and the workmanship. Because the interest is primarily in utensils and containers for domestic utilitarian service, the variable of greatest concern is strength: the ability of a ceramic to withstand the stresses of normal use without cracking or breaking.

When vessels are damaged they may be repaired and returned to primary use or converted to secondary uses, complex decisions that are highly variable from place to place (see, e.g., Arthur 2006: 102–20). Among the Gamo, non-potting villages tend to have more repaired pots than potting communities and, overall, one-fifth to one-third of the pots tallied in households were in secondary uses (Arthur 2006: 105, 120). In Chanal and Aguacatenango, Mexico, 21% of the household inventories were recycled vessels (13–18 vessels per household), with potters tending to repurpose vessels more frequently than non-potters in Chanal (Deal 1983: 179; see also comments on Afghan potters' multiple uses in sec.10.3).

Chipped or cracked rims might not detract from serviceability, whereas cracks that extend into the body are likely to affect the ability of the vessel to hold liquids. Damaged pots may be repaired and returned to primary use. Evidence of repair is sometimes visible on archaeological pottery by drilled holes: presumably these were made on either side of a crack, then twine was threaded through and tied to close the break and prevent spillage. If the pot held liquids, the crack and the perforations were likely filled with some substance, such as clay or lime plaster, pitch, or other material. The Roman writer Cato gave instructions for repairing cracks in the large earthenware storage vessels known as *dolia* by making a plaster of resin, wax, sulfur, and gypsum (Allen 1961: 77, 83; Younger 1966: 180).

Breakage is not the only reason a pot is removed from its original use: pots may be replaced (or recycled) because they are old and sour, changing the taste of the food cooked in them. Damaged vessels are often moved into a variety of secondary (and subsequent) uses (see DeBoer and Lathrap 1979: 125, 127). In some new functions—for example, as griddles or in the common switch from liquid to dry storage with age—they are essentially being recycled into new primary activities in the absence of production of new vessels. Recycled pots also may become planters, feeders for

animals, scoops, and so forth (see table 11.4). Damaged items may be stored for future use, especially along walls, at patio edges, or on roofs (Deal 1983: 193–96).

Broken pottery may be employed in architecture. In the Mediterranean region, amphorae were often reused by the Romans as lightweight fill in structure vaults (Lister and Lister 1987: 11, 320n17) and in the Maya lowlands the necks of jars were often inserted into the edges of doorways in elite residential structures to anchor ropes for hanging curtains. Sherds were reused in architectural refurbishment of structures in a small Pueblo village (Sullivan 1989).

Another common method of recycling broken vessels leaves ambiguous traces in the archaeological record—sherds may be ground into grog temper for use in pottery manufacture. This frequently involves destroying sherds from ancient middens (DeBoer and Lathrap 1979: 111; Stanislawski 1978: 222), but sometimes the sherds used are recent manufactures (e.g., Gosselain 1998: 101). No estimates are available for the number of sherds or vessels used this way or for how much sherd counts or weights might be distorted as estimates of total numbers of vessels.

Few data are available on the rate of replacement of broken vessels within households. Understanding this process requires data on the interval between breakage and replacement or, failing that, on the rate or intensity of production and the levels of sale or gift-giving within potters' households. Potters themselves are often vague about this subject; they replace broken household vessels from their regular output without thinking about it. Among the ten studied households among the Tarahumara of Mexico, two to four cooking pots are made each year, a large storage pot is made every other year, and the replacement rate is two or three pots a year (Pastron 1974: 101–2). Among the Huichol, roughly 1–10% of the assemblage is broken each year (Weigand 1969: 25). In Chanal, an average of 33.3 vessels was replaced in 30 households (Deal 1983: table 23). In Bé, an average of 3.14 pots per year (or 15%) per household are broken and enter the archaeological record, necessitating approximately 360 pots per year for replacements (David and Hennig 1972: 20–21).

Table 11.4 Recycled Uses of Damaged Pots or Sherds

Hopi-Tewa, Arizona[a]
Building into window or door frames of houses
Chinking walls or bread ovens
Tools in pottery manufacture
Protecting pots in firing
Placing in shrines
Divining the future
Templates for copying designs
Grinding for temper

Huichol, Mexico[b]
Animal feeders
Wax melting, candle dipping
Lids
Dustpans
Ladles or scoops

Shipibo-Conibo, Peru[c]
Grinding for temper
Pot supports
Griddles over fire
Chicken roosts
"Kilns"

Fulani, Cameroon[d]
Animal feeders (sheep and goats)
Tools for pottery manufacture
Cooking tripods

Pakistan[e]
Kiln construction
Grinding for temper
Liquid receptacles
Molds
Scrapers in pottery manufacture
Placing in paths in rainy season
Watering plants
"Intimate purposes"

Thailand[f]
Animal feeders
Frying pans
Dry storage
Water troughs
Children's playthings
Pot stands
Games

Chanal and Aguacatenango, Mexico[g]
Pot lids
Cutting boards
Mixing
Trash removal
Nests for fowls
Feeders
Seedling protectors
Watering plants
Paving material
Chinking walls
Storage containers
Toys
Bathwater containers

[a] Stanislawski 1978: 221–22.

[b] Weigand 1969: 23–24.

[c] DeBoer and Lathrap 1979: 111, 125, 127.

[d] David and Hennig 1972: 21.

[e] Rye and Evans 1976: 123.

[f] Solheim 1965: 259, 1984: 100.

[g] Deal 1983: 176–79.

The replacement rate of pottery is by no means equivalent to the production rate in a potting community, however, nor is it a constant one-for-one exchange (see Longacre 1985: 344–45). A shortfall between the need for replacement pots and those produced locally may be overcome by importing pots manufactured outside the community (David and Hennig 1972: 21).

Part 4

Methods and Measures: Analyzing Archaeological Pottery

> We should be aware that the pattern of specialization among archaeologists, which typically follows the division of ceramics, lithics, faunal remains, and so forth, does not necessarily correspond with that of the past producers whom we study. If archaeologists sort artifacts by material types in the field and simply leave them to respective specialists, they may overlook fundamental information from the overall assemblage.
>
> Inomata 2007: 130

Chapters in Part 3 emphasize what ethnographic data can tell us about making pottery. The eight chapters in Part 4 explore some of the many methods and approaches to analyzing the pottery, typically in fragments, that is recovered archaeologically. Analytical transitions between the pottery of the ethnographic present—its active use-life in systemic context—and the fragments constituting the archaeological record are not easy, and the theories, methods, and models proposed for such intellectual shifts continue to prompt debate.

Modern archaeological studies of pottery are based on four interrelated approaches: classification and dating, style/decoration, composition, and function/behavior. The first two approaches are traditional. Classificatory studies are still the nuts-and-bolts of fieldwork in creating and comparing categories of vessels or sherds representative of a particular culture at a particular time. The resultant groupings of styles and forms are the foundations of archaeological reconstructions of site histories and have played that role since the late nineteenth-century explorations of Sir Flinders Petrie in Egypt (1899).

Systematic studies of pottery composition and function are relatively recent. During the latter half of the twentieth century, advanced methods and instrumentation in the physical and materials sciences and engineering permitted the application of new analytical methods to archaeological pottery. These, along with extensive field programs in ethnoarchaeology, plus theoretical advances concerning the formation of the archaeological record, gave added impetus to the growth of innovative analyses, insights, and interpretations.

But the borrowing of these advanced techniques into the study of archaeological pottery, along with the “Wow! factor” of doing quantitative science in what had long been a qualitative field, necessitates several caveats and cautions. Many of them relate

to what is called middle-range theory in archaeology, analogous in many ways to translational research in biomedicine: finding practical applications. Four "translational" problems are summarized here, and examined in the following chapters:

- Equivalent conditions: In some senses it is fair to say that a clay is a clay. That is, other things being equal, a kaolin clay is a kaolin clay, whether in a village in Iraq in 6000 BC or in a scientific laboratory in the twenty-first century. The conditions for manipulating its behavior are very different, however. To take one example, firing, although it is undeniably useful to understand the behavior of clays under experimental conditions of time, temperature, and atmosphere in science and engineering labs, these conditions rarely simulate the complexity and variable characteristics of non-industrial pottery manufacture. For hand-built, non–kiln-fired, village pottery, the circumstances of fabrication and firing, and indeed the objectives of the entire operation, may be very different from those of contemporary manufactures or testing.
- Equifinality: The same outcomes can be achieved in multiple ways. Potters have many ways of combining resources, forming, and firing a clay pot to meet local standards for durability, and households have many ways to meet their needs for containers for preparing, serving, and storing food. Although laboratory tests of ceramic properties may suggest a single optimal solution, ethnographic and archaeological realities reveal numbers of them.
- Remnant properties: Characterization of an excavated ceramic provides information on its properties as they are today, hundreds or maybe thousands of years after it was originally produced and used. But various physical and chemical processes may have altered the original vessel during use and during and after discard. Thus the measurements obtained are the remnant or residual use-related properties, modified by any postdepositional alterations.
- Units of observation: Except for burials, caches, and other special contexts, archaeologists customarily work with fragments of pots rather than whole vessels. Translating potsherds into whole pots is more complicated than simply gluing, adding, and dividing, apart from the larger questions of transitions from pottery to behavior, and requires some understanding of the processes involved in breaking and discarding pottery.

Archaeologists study their pottery with many goals in mind, often simultaneously: dating sites, tracing trade patterns, understanding social and economic relations, and reconstructing ritual practices, among many other endeavors. The many seeds of method and theory sown in the past half century have begun to bear fruit, and the study of pottery currently benefits from a host of ideas and theoretical approaches that center on objects: *things* . . . which may be "wild" (Attfield 2000); which we can learn from (Kingery 1996); which have agency (Latour 2005), social lives (Appadurai 1986b), and histories (Lubar and Kingery 1993); and with which humans are "entangled" (Hodder 2012). "Stuff" (Miller 2010) and where it comes from (Molotch 2003). Possessions (Thomas 1999). More generally, the concept of materiality (Miller 2005) and its archaeologies (Meskell 2005) are playing a greater role in anthropology. Pottery and material culture in general are now better integrated into broader interpretations of the past, with new interpretations drawing on concepts and methods in the study of technology, behavior, social relations, and materiality.

A key problem in all aspects of pottery analysis and interpretation concerns sampling. Unless an entire site is excavated, a rare occurrence, the pottery recovered is a sample of the entire population of pots originally in use by the residents of the community. The nature of that recovered sample is a function of the strategy

implemented for sampling spatial contexts to determine loci for excavation of the site. With extremely large collections, it may be impossible to completely analyze all the sherds recovered, and in such cases the collection has to be subsampled. Issues of sampling and subsampling collections for particular purposes are discussed in the following chapters.

Finally, the pottery recovered at an archaeological site—like any other artifact category—does not constitute "data" until it is given meaning with reference to some larger context, such as a question, a hypothesis, or a model (Kaplan 1964). Further, data usually acquire such meaning through a series of observations about the items in question and these observations may be qualitative (e.g., pottery type, color, form, ware), ranked or ordered on some dimension, or quantitative (numerical, continuous, measurable). The chapters in Part 4 and also Part 5 are about making these kinds of observations.

12 Methods and Theories

> Data are always *data for* some hypothesis or other.
>
> Kaplan 1964: 133

Pottery analysis in the early twenty-first century is a mix of old and new. Historically, North American social anthropologists and others long disdained material culture studies (Miller 2010: 51). The "new" archaeology of the 1960s and '70s rejected trait-based and normative approaches in favor of processualism and ecology. The subjectivity and relativism of post-processual archaeology (Hodder 1985) countered the search for law-like generalizations with attention to agency theory, practice theory, gender, hermeneutics, phenomenology, social archaeology, and the like.

12.1 Theories and Approaches

Pottery manufacture, like other productive enterprises, is part of the broad engagement of humans with their environment through technologies for extracting and manipulating resources to meet individual and group needs. These interactions have been a touchstone for theoretical engagement in many subfields of archaeological investigation. In pottery studies, Frederick R. Matson's (1965a) ceramic ecology focused explicitly on this relationship (see also Arnold 1985, 1993; Kolb 1989; Kolb and Lackey 1988). A contextual approach to ceramic analysis, ceramic ecology seeks to place technical data into both an ecological and a sociocultural frame of reference by relating the technological properties of local resources to the production and use of the area's ceramic products (see Kolb 1989).

Like general cultural ecology, ceramic ecology begins with assessing the environment, including geology, hydrology, soils, vegetation, climate, and seasonal weather features (table 12.1) that might impinge on potters at a site or in a region (Arnold 1985, 1993). Of particular interest are local resources for pottery making, including clays, tempering materials, water sources, pigments, and fuels. The closest approximation of an early theory for ceramic studies, ceramic ecology provides a broad, integrated perspective on the role of pottery in a culture from archaeological, technological, and ethnographic viewpoints.

Table 12.1 Weather-Related Limitations on Pottery Making

Rainy season
Digging clay (mines may collapse or be flooded)
Too wet or cold to work comfortably
Drying pottery
Takes too long
Pots need protection
Firing pottery
Wind, rain, dampness, snow, frost
Greater losses
Fuel is wet
More fuel required, so costs increase
Conflicting demands (of agricultural activities)
Dry season
Pots dry too fast (cracking)
Greater demands for water vessels

Source: After Arnold 1985: table 3.2.

The ceramic ecology approach has been criticized along the same lines that cultural ecology was critiqued decades ago, as narrow determinism or possibilism (Gosselain 1998: 80). But ceramic ecology does not posit that the physical environment controls pottery making. Instead, it establishes some of the circumstances within which potters' decisions may be supported or constrained as they practice their technologies. Besides contextualizing the activity of pottery making, the environment also has an underlying role in vessel function with respect to the kinds of foods consumed and their preparation, including the availability of drinking water.

12.1.1 Experimental Archaeology and Ethnoarchaeology

Experimental archaeology and ethnoarchaeology, born in the 1950s as "action archaeology" (for history, see David and Kramer 2001: 6–32), became increasingly popular in succeeding decades. Experimental archaeology involves the manipulation of raw materials and tools pertaining to an archaeological context of interest to replicate the conditions of their production or use or both. The procedures of ceramic ecology, combined with the collection and testing of clay resources, can be included in this

activity. For many archaeologists and ethnoarchaeologists interested in pottery, collecting samples of local clay and other resources and experimenting with them in the laboratory has become standard operating procedure, irrespective of whether a ceramic ecological approach is explicitly acknowledged.

Comparison of the experimental findings with the properties of the pottery of interest contributes insights into potters' behavior in fabricating their wares and the functional characteristics of the final products (see Goulder 2010). The samples also serve as comparative material for provenience studies. Much of what was learned about the physical, mechanical, and thermal properties of pottery came from applying the techniques of materials science to archaeological pottery (e.g., Bronitsky 1986; Bronitsky and Hamer 1986; Feathers 1989, 2006).

Ethnoarchaeology is a more encompassing term for the body of method, theory, and data underlying such analogical and experimental comparisons. Ethnoarchaeology has been defined and redefined over the years, but essentially it is an anthropological research strategy (not technically a method or theory) involving studies of material culture and related behavior in living contexts, and their relations to the archaeological record (see David and Kramer 2001: 2, table 1.1). What may be the first ethnoarchaeological monograph was based on Maya pottery (Thompson 1958).

Because so many reconstructions of ancient life—especially chronological and intersite relations—are based on ceramic data, the wide range of ethnoarchaeological concerns allows archaeologists to address major methodological issues essential to these interpretations. Relevant matters, beyond understanding the nature of variability in ancient ceramics and their relation to function, include the socioeconomic arrangements for producing and distributing pottery, and the relations between the manufacture and use of pots and the formation of the archaeological record. Pottery was the focus of two productive long-term ethnoarchaeology research programs, one among the Kalinga in the Philippines (Longacre 1991; Longacre and Skibo 1994) and one in the Maya highlands of Chiapas, Mexico (Deal 1985, 1998). Other projects are continuing this approach, for example in Africa (Gosselain 1994, 2000, 2010; Gosselain and Smith 1997). The state of ceramic ethnoarchaeology has been assessed in multiple reviews (D. Arnold 2003; P. Arnold 2000, 2003; Costin 2000; David 1992; Hegmon 2000; Kramer 1985; London 2000; Skibo 2009; Stark 2003; see also Roux 2007), and the general subfield of ethnoarchaeology has had its own eponymous journal since 2009.

A repeated critique, stated in various ways, is that ethnoarchaeology lacks an overarching body of theory that would allow it to move beyond descriptive detail—and the early cautionary tales for which it was initially famous—and focus on cross-cultural regularities (e.g., O'Connell 1995; Roux 2007). One proposed solution to this problem is evolutionary archaeology, also known as neo-Darwinism or selectionism (e.g., Lyman and O'Brien 1998; O'Connell 1995; see also Hodder 2012:139–44; Loney 2000). Two distinct research traditions are subsumed in this approach, one focusing on human behavioral ecology and natural selection, the other centering on cultural transmission,

cultural traditions or "lineages," and dual-inheritance theory (Shennan 2008). For selectionists, "anthropological theory is largely irrelevant" whereas those interested in dual inheritance incorporate both anthropological and evolutionary theories (Stark et al. 2008b: 6).

More traditional social theories have continued to predominate in pottery studies, and evolutionary perspectives have not yet generated great enthusiasm (cf., e.g., Bowser and Patton 2008; Neff 1992a, 1993, 2006; Neiman 1995). But both ethnoarchaeologists and evolutionary archaeologists are increasingly focused on foundational questions of learning strategies and cultural transmission of material technologies (e.g., Gosselain 2011; Hayden and Cannon 1984; Stark et al. 2008a).

12.1.2 Technology and Choices

Increased attention to objects and materiality has been accompanied by greater anthropological interest in technologies in general (e.g., Dobres 2000; Lemonnier 1986, 1992; Pfaffenberger 1988, 1992). Two closely related approaches, borrowed from other artifact media, have been productively applied to archaeological pottery. One is the *chaîne opératoire* (operational sequence) approach, developed in André Leroi-Gourhan's studies of Paleolithic stone tool manufacturing (see Bar-Yosef and Van Peer 2009; Lemonnier 1976). The other focuses on technological choices (Gosselain and Livingstone-Smith 1995; Lemonnier 1993). As applied to pottery, these approaches address manufacture: identifying and assessing potters' choices in selecting and preparing resources, forming, decorating, and firing a vessel.

But potters' choices are not free: the "notion of choice is purely theoretical" (Gosselain 1998: 105n7), choices are set within a decision hierarchy (Carr 1995: 215–30), and they often represent compromises (P. Arnold 2007: 89–94). Choices are framed and contextualized by multiple constraints, locational (environmental), material (resources available), technological (tools and skills), socioeconomic (tradition; consumer preference), and functional: the overarching "effectiveness" of the pot (Hayden 1998: 4–7, 41–42). In addition, choices may be influenced by other technologies or practices, and previous choices may constrain subsequent ones (the decision hierarchy). Many constraints are culturally embedded, reflecting the local ceramic ecology (locational and material) plus traditional, customary values (Reina and Hill 1978; see also Sillar 2000: 43, 57–58; Sillar and Tite 2000).

Accustomed motor patterns—habitual postures and actions—are a particularly powerful force for maintaining tradition in pottery manufacture. Motor patterns resist change because they relate not only to the positions in which implements are manipulated, but to the shapes and sizes of the implements themselves. With respect to pottery, the conservative force of motor patterns is most significant in forming vessels and in using them. Forming pottery vessels, whether by coiling, molding, or throwing, requires a highly coordinated set of movements learned by experience over a long

period, along with eyes and fingers trained to recognize appropriate texture, thickness, and smoothness of the clay at various stages. All these are part of what Pierre Bourdieu (1990) called *habitus*, the shared, underlying, unconscious skills, tastes, memories, and knowledge that provide structure and order in everyday life.

As in the case of decorative styles of pottery (chap. 24), there are concerns about whether potters' selections of resources and procedures are conscious or unconscious (P. Arnold 2007: 90–94; Carr 1995: 221). At how deep a level does "culture" operate on technology: is it deeper than individual choice? Cultural tradition likely operates at different levels or degrees in different societies, and may affect varied technologies or productive activities—or even particular vessel forms (e.g., Zulu jars for brewing beer; Fowler 2006)—in different ways.

Taken together, traditions, resources, and human creativity create a menu of potential selections, but they do not present an infinite array of options and opportunities. Moreover, archaeologists cannot know the menu available to potters in antiquity: we can only know or infer parts of it. What we see today, therefore, is not the array of choices open to potters but rather the outcomes—behavioral, material, technological, functional—of their *decisions*.

Two other strategies are related but lack some of the pitfalls related to the choice approach. The concept of technological styles, developed with respect to metallurgy (Lechtman 1977), incorporates materials and behavior, interrelating specific patterns of exploiting particular kinds of resources in customary ways. Like other kinds of styles, technological styles communicate information; as such, they are symbolic systems containing information about the society that not only manufactures but also uses the items in various ways, in various contexts. A second approach is design theory (Carr 1995; see also Kingery 2001). One variant (Hayden 1998: 4–11) emphasizes the creation of an object as a solution to a "problem" or need (e.g., a rodent-proof container; a vehicle to travel to Mars). The primary goal of design is the final object's effectiveness or ability to perform as intended given the contextual field of embedded constraints.

12.1.3 Behavioral Archaeology and Life Histories

The behavioral archaeology approach of Michael Schiffer, his students, and his Laboratory of Traditional Technology (Schiffer 1972, 1976, 1987, 1992, 1995, 2010; Schiffer and Skibo 1987; Schiffer et al. 1994, 2001; Skibo and Schiffer 1995, 2008; Skibo et al. 1989) has garnered wide support. These archaeologists have applied experimental archaeology to myriad issues of ceramic technology, vessel performance, and site formation processes over the years. James Skibo (2008, 2009: 41–44), for example, has woven the many threads of behavioral archaeology, ethnoarchaeology, and technology into a performance-based life-history approach to material culture.

The life-history approach—variously phrased in terms of objects' cultural biographies (Gosden and Marshall 1999; Kopytoff 1986; Shott 1996) and social lives (Appadurai 1986b; see Blanco-González 2014)—is related to recent interest in materiality and technology, combined with agency theory. From this life-cycle viewpoint, material culture, including pottery, is considered not to be literally alive, but rather to have interacted with humans in varied social, economic, and political contexts from the time of manufacture until discard (see also Latour 2005).

The real contributions of ethnoarchaeology—and also the underlying premise of materiality studies—lie in exploring relations between people and things rather than in merely providing analogies, and these relations should be developed into models directly applicable to the archaeological record (Skibo 2009: 31–32, 36). Addressing ceramic ethnoarchaeology in particular, Skibo (2009: 33–34) recognizes that the significant issue for archaeologists is the "disjunction in units of observation" (that is, whole pots versus sherds) and thus the fundamental problem is how pots break and enter the archaeological record. In broader terms, the issue of interest concerns the "site formation processes" underlying that record.

12.2 Formation Processes

Archaeological sites are created by multiple processes, cultural as well as noncultural or environmental. These processes, and the transformations artifacts undergo during them, are known as site formation processes. Cultural site formation processes are human behaviors "that affect or transform artifacts after their initial period of use in a given activity" (Schiffer 1987: 7). These processes have been conceptualized as a movement of artifacts out of systemic context, or engagement within a cultural system, and into archaeological context through abandonment, loss, and discard (Schiffer 1972). Noncultural processes, such as decay and natural disturbances (e.g., floods, bioturbation, erosion), are largely outside the present concerns. Both cultural and noncultural processes "(1) transform items formally, spatially, quantitatively, and relationally, [and] (2) can create artifact patterns unrelated to the past behaviors of interest" (Schiffer 1987: 11).

Human behavior, including cultural formation processes, creates various archaeological units of study. One such unit is an assemblage: a collection of artifacts of single or multiple media that are temporally and contextually associated in a single provenience. That provenience may be as small as a single burial or a trash deposit, or as large as a house or an entire site. With respect to pottery, archaeologists use not only whole vessels in interpreting the archaeological record, but also the massive quantities of broken fragments (sherds) recovered in excavations.

Making sense of these huge sherd collections is of interest for a variety of descriptive, inferential, and inter- and intra-site comparative purposes (Keighley 1973; Orton et al. 1993). For example, it may be desirable to know what proportion of the pottery from a site represents serving wares versus cooking pots, or how much was imported rather than locally made, or whether elite residents of Site A had more of a particular kind of tradeware than did non-elites, or more of it than did elites at Site B. Similar questions are also relevant to studying vessel function and economic activities such as production and trade, and in estimating the extent and duration of occupation at a site.

Such questions about ceramic assemblages, whether phrased in terms of absolute quantities of sherds or of relative amounts such as ratios or proportions or percentages, are deceptively simple. Because ceramics constitute such a large proportion of the artifactual material recovered at archaeological sites, their behavior in site formation processes has been the focus of considerable ceramic ethnoarchaeological research. (Ritual behaviors that may result in specialized mortuary or other kinds of subassemblages are excluded here.)

12.2.1 Discard and Refuse Disposal

Ethnoarchaeological studies reveal that pottery discard behavior and refuse accumulation and disposal are more complex than was initially apparent to archaeologists. The processes of discard and the resultant deposits have been described in different ways for analytical purposes (Staski and Sutro 1991). Discard behavior, for example, can be distinguished as maintenance (e.g., sweeping a house), temporary or provisional, and permanent (Deal 1985). Refuse deposits have been described as de facto (objects left on living surfaces after abandonment), primary (discard at or near the use location), and secondary (moved from a primary location, as by sweeping) (Schiffer 1987: 18; Wilson 1994). Permanent deposits, disposal areas, or dumps for primary and secondary refuse are called middens (Needham and Spence 1997). At least one study has distinguished different types of middens: household, local, and communal (Beck 2006b: 38–39).

The discard behaviors that create these deposits vary. Some behavior may be described by principles of minimization of effort or least cost, with pottery disposed of fairly close to where it was used and ultimately broken or damaged. Other studies suggest fairly wide dispersal. Sweeping may concentrate sherds in midden areas at the peripheries of household compounds (see Deal 1983: 197; DeBoer and Lathrap 1979: 128–33), but fragments may be found anywhere from 5–10 m to 100 m away from residences (Beck 2006b: 38–41; Pastron 1974: 108–9; Weigand 1969: 24, 26). Recent "fragmentation studies" propose that many artifacts, particularly early figurines, were intentionally broken, the fragments deliberately scattered at a site, given to others as symbols of social relations, or accumulated into "sets" (Chapman 2000; cf. Brittain and Harris 2010).

Still other studies record disposal patterns related to considerations of the meaning or symbolism of the refuse. In Thailand, distribution of refuse has been related to patterns of storage within households, with prestige wares such as porcelains and celadons being stored in sleeping areas, away from traffic (Solheim 1984: 100). Postclassic lowland Maya temples were ritually swept or cleansed after a ceremony, the material recovered archaeologically in primary discard deposits behind the structures.

The extent to which these behavioral and depositional patterns are cross-culturally valid in archaeological contexts is of interest. Primary and secondary midden discards of pottery are typically distinguishable archaeologically by degree of weathering or sherd size (see Beck 2006b: 37). Differences in sherd frequencies and sizes as a result of comminution along pathways, as opposed to normal refuse deposits (DeBoer and Lathrap 1979: 133 and n14; see Solheim 1984: 102), and other taphonomic considerations (Reid 1984; Felgate et al. 2013), add to problems of quantifying sherd materials. At Classic Maya sites, midden debris was commonly incorporated into construction fills of platforms and temples.

Another variable is topography. Midden discard patterns in Dalupa (Philippines) are at least partially a consequence of the village's location on a steeply sloping hill,

inaccessible by vehicle (Beck 2006b: 31). In the Maya highlands, trash is commonly dumped down ravines (Hayden and Cannon 1984: 146), a long-standing pattern disconcertingly evident on the southern outskirts of Guatemala City on final approach into the airport. To what extent are such discard patterns translatable to communities in flatlands?

12.2.2 Site Assemblages

The many uses of pottery vessels raise questions about the numbers and kinds of utensils that constitute ceramic assemblages at household or structure and site or community levels. An archaeological ceramic assemblage is commonly defined in two ways. One is as a domestic assemblage associated with an individual household or households, which may or may not include noncontainer artifacts (figurines, whistles, toys). Data come from ceramic inventories, although there may be questions about whether and to what extent a small excavated sample is generalizable to an entire site of unknown socioeconomic composition. Alternatively, a ceramic assemblage may be defined site-wide using total sherd or vessel collections, as, for example, an assemblage characteristic of a particular temporal interval. These may be subdivided into various kinds of subassemblages (e.g., elite, mortuary, ritual, domestic). Ceramic inventories and studies of related patterns of use, reuse, and discard provide a basis for investigating site formation processes, or formation of the archaeological record (see, e.g., Bollong 1994; Fowler 2011; Frankel and Webb 2001).

12.2.2.1 Population and Permanence

Archaeologists have borrowed and adapted, implicitly and explicitly, the data from ceramic ethnoarchaeology in varied approaches to understanding the ceramic assemblages of historical and prehistoric sites (e.g., Mills 1989). Two early goals were to estimate the number of residents in a household or site and to estimate the length or permanence of occupation of a structure or a site (the latter now known as accumulations research; e.g., Varien and Mills 1997; Varien and Potter 1997). For these goals, researchers used data from ethnographic ceramic inventories, which provided information on the number of pots per household, the rate of replacement of broken pots, and the number of persons per household.

In general, estimating populations at any archaeological site is a dicey proposition, requiring multiple separate determinations, each involving assumptions that may or may not reflect ancient realities, in addition to questions about the relations between the excavated sample and the sampled population (the "parent population" of a sherd sample; see Felgate et al. 2013). Calculations include establishing how many (or what proportion of) structures (or rooms) were residential (as opposed to having storage or ritual functions, for example), how many (proportion of) residences/rooms were contemporaneously occupied, and how many people occupied each residence/room.

Using archaeologically recovered pottery as a basis for calculating or simulating the length (permanence) of occupation or the population of a site requires further estimates or calculations, each with its own assumptions and variables:

- The total number of pots in active use per household at any time;
- The rate of replacement of broken pots; and
- The total number of vessels from residential contexts. This estimate is calculated from the sherds recovered in excavation and may be based on total sherd counts, rim and base counts, sherd weights, or more complex procedures using combinations of these measures, depending on the nature of the collection.

The first two estimates benefit greatly from the past few decades of ethnoarchaeological research and ceramic inventories (sec. 11.2). The first, the number of whole pots per household or the composition of the household assemblage, is highly variable. Although every household has to meet more or less similar domestic needs, the ways these needs are met by means of pottery can vary considerably, depending on multiple factors, including multiuse vessels, recycling, and the use of containers made of other materials, such as wood, skins, fibers, or gourds, or today's plastics, glass, and metal. The second estimate, the rate of replacement of broken pots, might seem to be a relatively simple matter of householders' making or acquiring a new pot whenever one cracks or breaks. Instead, however, it is a complex and decidedly not straightforward process involving production, use, repair, and reuse/recycling of the vessels before discard (see Sullivan 2008). A fundamental question is that of the use-life of pots, which varies depending on multiple factors, particularly size/weight and frequency of use (see Varien and Potter 1997: 200–201). Re-analysis of the use-lives of 862 Kalinga pots over a thirteen-year period ranged from less than a year to nearly seven years, for an average of 2.2 years (Tani and Longacre 1999: table 2).

One early estimate of household size based on ceramic data employed vessel volume capacities, specifically ratios of cooking-jar capacity to serving-bowl capacity at Pueblo sites in northwestern Arizona (Turner and Lofgren 1966). The underlying assumption was that a cooking pot represented a household unit of food preparation and consumption, and was used to prepare serving bowlfuls of food for a certain number of persons in that household. Ladles had a mean capacity of 360 cc (approximately one and a half cups); bowls had a mean capacity of 691 cc or two ladles; and cooking jars had a bimodal distribution, with peaks above and below 8000 cc (Turner and Lofgren 1966: 124–25). The sizes of households estimated by these jar-to-bowl ratios ranged between 4.4 and 5.1 persons and, multiplied by numbers of rooms at individual Pueblo sites, could yield estimates of the total site population. This hypothesis was tested ethnoarchaeologically in the Maya highlands (Nelson 1981), exposing a multitude of intervening variables in the hypothesized correlation . . . although it might be questioned whether highland Maya households provided an appropriate analogy to Pueblos.

12.2.2.2 Some Cautions

Ethnographic data suggest certain cautions in inferring the composition and functions of vessel assemblages in archaeological contexts, and these difficulties must be recognized and confronted. The primary problem is that archaeologists usually begin with ethnographic or ethnoarchaeological data in which the function of the pot is already specified (it is an independent variable) and the shape and technological properties (effectively dependent variables) are often incompletely described. In analyzing prehistoric specimens, however, archaeologists essentially have to work backward, retrofitting their technological and shape data (archaeologists' independent variables) into retrodictive tests of hypotheses of vessel function (function then becoming a dependent variable).

Such transformations are empirically and methodologically specious for several reasons. One is that the relations between form and function in these studies constitute theories to be tested rather than empirical givens. In addition, shape, composition, firing, and such, are consequences of many constraints on the potter's behavior, not simply dependent variables reflecting or predicting the vessel's intended use.

Furthermore, the inferential problems caused by real-world determinants of assemblage variability are of course multiplied in antiquity, because archaeologists rarely excavate entire sites and therefore rarely have access to an entire ceramic assemblage representing the full range of socioeconomic statuses at a site. The average numbers of vessels or kinds of vessels per household may differ among social groupings in a region. For example, there may be differences between potting and non-potting households, or in potting versus non-potting communities, or in communities with varied social, economic, religious, or ethnic backgrounds. Variation in kinds and numbers of vessels may be related to environmental features, such as proximity to water sources and the need to store water, or to seasonal availability of particular foods. In many areas and times, assemblages may differ depending upon whether a site was permanently or only seasonally occupied (e.g., Braun 1980; Shapiro 1983, 1984).

Reconstructions of archaeological ceramic assemblages and functions are thus fraught with uncertainty, because variability may be explained by status, function, size, ethnicity, and many additional complex factors. Although knowledge of these factors can be used to retrodict the composition of a ceramic assemblage in a particular inventoried ethnographic household (e.g., Nelson 1981), they cannot so easily be used to *pre*dict the individual ceramic vessels that will be recovered in an unknown archaeological situation or draw precisely the same conclusions from their presence. Determining the specific functions of each vessel had been even further removed from certitude, but the findings of experimental and other functional analyses (see Skibo 2013 for a review) permit more reliable assessments.

In this light it is useful for archaeologists to calculate and compare the relative percentages of different vessel forms for individual households or individual sites. The bulk of the assemblages may or may not comprise basic vessel forms. The variability and diversity of formal and functional categories in these assemblages can be expected

to vary not only with the considerations of use, activity, and status identified above, but also with the focus of ceramic production in the society and with the possible existence of resources with special properties. At the same time, it must be remembered that the need for increased container volume might be met either by more pots or by larger pots, and thus larger households might have either more pots or larger pots (or both) than smaller households.

Household assemblages may also vary with the general level of sociocultural complexity. Complex societies have more social, economic, or ethnic components (or statuses, identities), each of which may have its own special container-related needs and activities, particularly dietary, and modes of satisfying them (see Otto 1975). Societies at lower levels of complexity—whether measured by sociopolitical, economic, or demographic parameters (including non-sedentary settlement)—may have a smaller range of vessel form categories, fewer specialized forms, more overlapping of functions, and greater emphasis on the primary all-purpose or multifunctional forms. But these kinds of generalizations, while intuitively attractive and even plausible, need to be empirically tested.

13 Classification

> A homogeneous group is one that has not attracted the attention of an investigator.
>
> Benfer 1975: 246

Classification, phrased most simply, is the gathering of similar entities. Classification is a basic activity in all scientific disciplines—in which it is often called systematics—to express the structural relations underlying its subjects of study. Moreover, classification lies at the core of humans' participation in the real world. Human cognition includes fundamental processes whereby different kinds of things are identified, organized, and named, as in distinguishing among members of the categories human, dog, tree, and rock.

The objective of a classification exercise is to create groups whose members are very similar (high within-group homogeneity) while the groups themselves are very dissimilar (low between-group homogeneity). The principle is that the similarity of entities within groups is not a matter of chance but reflects something significant about them. In classifying pottery, anthropologists and archaeologists commonly approach their subject matter from three directions: folk (emic) classification or ethnotaxonomy, devised (or formal, scientific, etic) classification, and form-based groupings.

13.1 Attributes

Analysts create groupings of entities on the basis of commonalities called attributes or variables. An attribute is a property, characteristic, or feature of an entity, typically one of material, technique, style, or morphology. In the analysis of pottery, variables of interest include color, thickness, inclusions, hardness, form, and so on. An attribute state is usually an artifact's specific value or score on a particular attribute; for example, the states or values of the attribute "color" may be red, black, white, or brown; values for the attribute "hardness" may be 1.5, 4.0, or 6.5; values for mica might be present or absent. (The terms attribute and attribute state are sometimes employed interchangeably, with attribute occasionally referring to the state or value of a particular variable.)

Attributes themselves are often classified by their role or utility in a devised classification. For example, attributes of archaeological pottery may be described as intrinsic, including an object's composition, shape, and decoration, or extrinsic, such as its date, provenience, and inferred function as assigned by the archaeologist (Gardin 1980: 65–68). Or, attributes can be ranked as key, essential, and inessential according to their significance and utility within a particular devised scheme (Clarke 1968: 71).

Although it is sometimes claimed that to be valid classifications should account for all attributes, this is patently impossible. No matter how many attributes are considered in any classification system, the number that theoretically exists is infinite (see Hill and Evans 1972: 250–51): one need only think of incorporating all qualitative and quantitative characteristics (attribute states) of all major, minor, and trace chemical and mineral constituents (attributes) of a pottery paste to realize the impossibility.

Modes are certain attributes the analyst judges to reflect communitywide standards or expectations for manufacturing and using the ancient artifacts. As defined by Irving Rouse (1960: 313; see also Taylor 1983: 129–30), a mode is "any standard, concept, or custom which governs the behavior of artisans of a community, which they hand down from generation to generation." Modal analysis represents an effort to achieve some isomorphism between categories of devised classifications and those of the ancient makers and users of the pottery—that is, to replicate ancient folk classifications. Not all attributes of the artifacts represent modes as originally defined, however.

Two kinds of modes may be discerned, both intrinsic. Conceptual modes relate to the style or form of the object, such as red slips or tripod supports. Procedural modes relate to manufacture and include particular kinds of temper or the use of molds or coiling techniques (see Rouse 1960: 315). Other than temper, attributes pertaining to the composition of the pottery typically have not been considered modes, doubtless at least partly because pottery composition was not of major interest at the time this terminology was developed. Closer attention to modes of technology and composition is essentially the basis for identifying technological styles and choices/decisions.

13.2 History of Americanist Pottery Classification

Classification has long been of major—perhaps excessive—interest among North American anthropological archaeologists, having played a key role in the intellectual history and operational practice of the field since the late nineteenth century. Major stages in the development of Americanist archaeology have been termed the "classificatory-descriptive" and "classificatory-historical" periods because of the emphasis on these operations for describing and organizing vast quantities of data (Willey and Sabloff 1993). This history illustrates some of the broader issues and controversies surrounding the development and procedures of classification in the discipline.

Beginning in the 1920s and 1930s, elaborate schemes for classifying artifacts, sites, and cultures were developed for chronological-comparative purposes in the Southwestern United States. The procedures for identifying, describing, and naming pottery types during this period established the foundation for many concepts used today. One of the first statements of what constitutes a type was offered by the Pecos (New Mexico) Conference in 1927: a type was defined as "the totality of characteristics which make a given ceramic group different from all others" (Kidder 1931: 21–22; a view essentially aligned with what is now known as the attribute-cluster position, below). This conference also developed the binomial system for naming pottery types (Kidder 1927: 490), analogous to the biological system of binomial nomenclature, whereby type names combine a geographical place (e.g., Tularosa or Jeddito) with a technically descriptive term. The latter term may refer to surface treatment or color (incised, black-on-white, polychrome, plain, etc.) or technology (coarse, thick, etc.).

In the early 1950s, a major dispute erupted concerning whether types are inherent in the data and merely recognized by analysts or whether they are artificial units imposed on the data. James A. Ford's (1953) pivotal publication "Measurements of some prehistoric design developments in the southeastern states" argued that pottery types were analytical constructs created by the archaeologist as tools for chronology-building and, more important, for achieving an understanding of culture change. The position had been established somewhat earlier (Ford 1938), and indeed a classic statement of this view had been made in 1946, some years before the Ford monograph, by J. O. Brew, who argued:

> We must classify our material in all ways that will produce for us useful information. . . . We need more rather than fewer classifications, different classifications, always new classifications, to meet new needs. We must not be satisfied with a single classification of a group of artifacts or of a cultural development, for that way lies dogma and defeat.
>
> *(Brew 1946: 65)*

According to this viewpoint, types are analytical and descriptive constructs, devised or created by archaeologists to determine the structure of variability in their data and to investigate particular problems.

Ford's stance was challenged in Albert C. Spaulding's review of his monograph, published separately as a manifesto entitled "Statistical techniques for the discovery of artifact types" (Spaulding 1953a, 1953b, also 1982). In his view, types are nonrandom attribute associations inherent in a data set that archaeologists can discover through statistical correlation techniques. This view of types as "real" and inherent in the data had been articulated earlier in one form or another by several scholars (e.g., Krieger 1944; Taylor 1983: 130) and its popularity continued in subsequent decades.

Taking their cue from Spaulding, archaeologists began closer investigation of quantitative approaches for bringing order out of their observations. In the late 1960s and early 1970s, numerical taxonomic (Sokal and Sneath 1963) and multivariate statistical techniques gained increasing attention for organizing large data sets by similarities and differences in multiple attributes simultaneously (see Ammerman 1992). Many factors were responsible for this interest: the objectivity or neutrality of statistical methods, the growing availability of computers, an increasingly rigorous scientific focus of archaeology as a whole, and attention to a much wider range of attributes in artifact collections as classifications began to be expected to do more than date sites. All contributed to a need for more sophisticated systems for investigating the structure of complex data sets.

However, although Spaulding's work had emphasized that types were discovered by correlating attributes, these quantitatively based classifications were not invariably interpreted in the vein of inherent types. Instead, they were usually regarded as created rather than discovered clusters of items rather than attributes (e.g., see Hodson 1982). In this alternative view, a type is defined as a group or class of items that is internally cohesive and can be separated from other groups by one or more discontinuities in attribute states (Whallon and Brown 1982: xvii). This view gained strength with the changes in archaeological method and theory in the 1960s and rejection of normative orientations in favor of positivist models (see Binford 1965; Hill and Evans 1972). In addition, with the greater precision of chronometric dating techniques, the need to direct pottery typologies solely toward chronology-building diminished, as did the often rigid classificatory schemes associated with this objective.

As archaeology developed research goals other than chronology and comparison, new aims of pottery analysis emerged, including determination of function, production, residence patterns, socioeconomic relations, and ritual, and these put a premium on innovative approaches to classification and on problem-oriented typologies. Investigators often developed their own categorizations of pottery to address their specific questions, and these were frequently based on vessel forms (morphological types), long used in classifications in Europe and Asia.

13.3 So, What Are Types?

Classificatory operations in archaeology aim to create "types," and variations in the definition of a type arise from different positions on how they may be created (Adams and Adams 1991; Cowgill 1982; Hill and Evans 1972; Whitaker et al. 1998; Wylie 1993). As noted, one position is that types are inherent in objects and discovered through statistical clustering of attributes (Spaulding, Kreiger, Rouse, Taylor, Whallon); another is that types are created, constructed and imposed clusterings of attributes (Ford, Brew, Dunnell). The object-based position is not totally opposed to the attribute-based definition, however, because types still depend on attributes (and hence indirectly on their associations) rather than on a single attribute. Regardless of which position is taken, attribute associations are empirically real, discoverable, and verifiable. And in any case, the question of whether types are real or artificial/imposed is poorly phrased (Hill and Evans 1972: 261): any artifact class formed by associating two or more attributes or attribute states—regardless of whether these associations are determined statistically or by eyeballing—can be considered to represent patterned behavior on the part of earlier peoples. This patterning may or may not correspond to explicitly held notions (so-called mental templates: conscious or unconscious choices or decisions) concerning the artifacts.

The salient issue, therefore, concerns the archaeologist's selection of the attributes used to seek associations. Because it is impossible to consider all attributes of any entity, some decision has to be made. It is this selection that governs the nature of the resultant classes, and thus different types with different meanings arise from the particular attributes chosen to determine the group divisions. Different kinds of attributes lead to different kinds of types—for example, historical-index, functional, cultural, and morphological (Steward 1954). Attributes are selected either because they are germane to a particular problem or they are based on some consensus concerning their role within a given classificatory scheme (e.g., the type-variety system).

In addition, attributes may be (and often are) employed hierarchically rather than simultaneously to create types in a collection (see Whallon 1972). Because the types formed are an artifact of not just the archaeologist's attribute selection but also this ranking process, it is pointless to argue whether a single classification is the best or only one for a particular data set (see Read 1989).

13.4 Kinds of Classifications

13.4.1 Ethnotaxonomy

The people who make and use pottery in their daily lives have indigenous terms for their vessels, in the same way today's English-speakers distinguish among frying pans, mixing bowls, salad plates, teapots, and coffee mugs in our own kitchens. Anthropologists and archaeologists refer to indigenous groupings and names as folk classifications or ethnotaxonomies. Ethnotaxonomy is part of the field of inquiry called ethnoscience, which addresses the structuring of cognitive domains—the boundaries and terms used by some group of people in organizing their surroundings (see Werner 1972).

Like terminologies of the modern Western world, folk classifications of pottery are based on several characteristics, primarily shape and size (see, e.g., Fowler 2006), and may emphasize attachments such as handles or spouts. They also call attention to intended use and contents: the general functions of cooking, storage, or serving as well as the kind of good prepared or served, liquid or dry. For example, in Kathmandu a great deal of variation exists both within and between classes:

> In terms of actual measurement the three classes [of liquid storage jars] could overlap quite considerably whereupon I was told that it was a combination of shape and size; when I pressed further in attempting to identify the precise shape variations concerned, i.e., flat or round base, rim forms, nothing could be selected as a permanent and identifying shape characteristic of one or another. However, the fact remains that all agreed instantly on names for any given pot.
>
> *(Birmingham 1975: 384)*

Box 13.1 Classification Terminology

It is important to understand differences among and between the terms groups, classes, and types, which are sometimes distinguished at different stages or levels of the classification process (fig. 13.1; see Dunnell 1971):

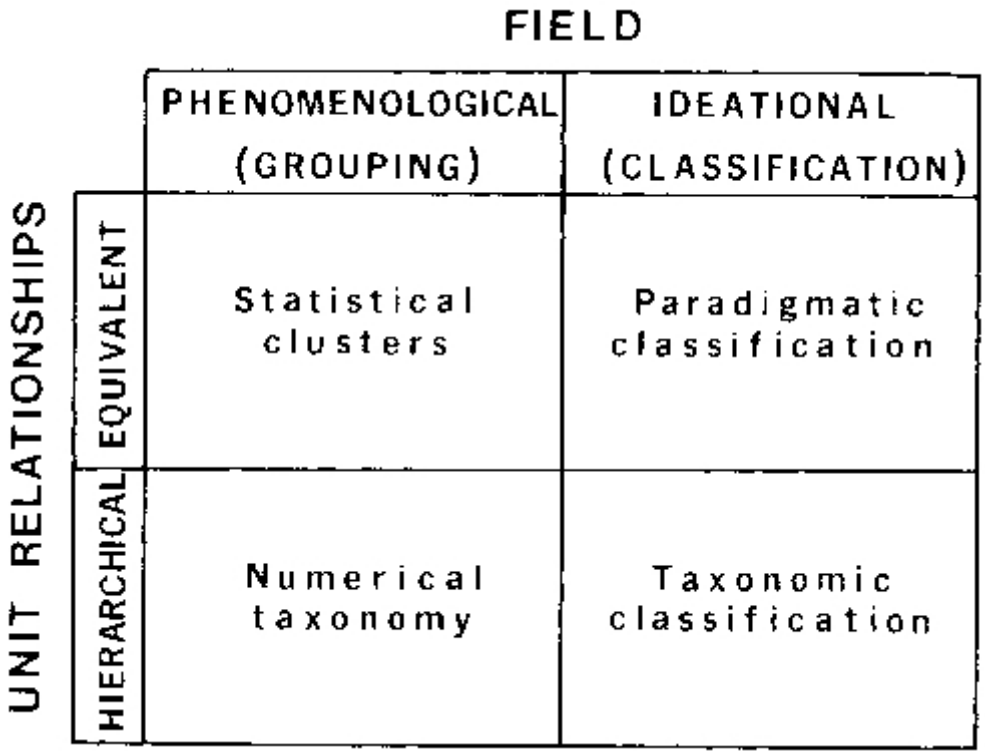

Figure 13.1 Model of different methods for ordering objects and events by classification versus grouping procedures. After Dunnell 1971: fig. 9.

- A group consists of actual objects, such as potsherds, and exists in the phenomenological or empirical realm, specific to a time and a place. Different kinds of groupings—which also represent different levels of classification—may be distinguished. The concepts and objectives of these processes may overlap, so they are not always mutually exclusive:
- Categorization refers to creating groups for a new and previously unclassified set of materials.
- Identification is a process of assigning individual objects to established classes previously defined by certain criteria or properties of their members. {~?~TN: This second and third item should constitute a sublist.}
- Classes and types are cognitive constructs. They represent verbal models or concepts about categories of objects and their attributes and thus they are ideational, and independent of time and space (Hill and Evans 1972: 233):
- A class is a "generic term referring to any division of materials into groupings based on similarities and differences" and may be based on single attributes.
- A type is a formal conceptual (or abstract) unit based on "a consistent patterning of attributes of the materials."

The differentiation between the empirical (group) and the conceptual (class and type) is highlighted by a further distinction, that between classification and typology (Kluckhohn 1960, cited in Gifford 1960:

346; see also Gardin 1980: 63):

- A classification is "a set (or sets) of empirical groupings established for convenience."
- A typology is a kind of classification, one that is theoretically oriented and "directed toward the solution of some problem or problems."

Furthermore, one can distinguish different kinds of classifications by noting, for example, whether the criteria (attributes and attribute states) for describing classes are equivalent and unordered, nonequivalent and ordered, or hierarchical (fig. 13.1; Dunnell 1971: 70):

- Paradigmatic classification is a process of creating equivalent units and takes place in the ideational realm. An example in pottery analysis is categorizing vessels by certain features such as form: bowl, jar, plate, and cup are equivalent, unordered dimensions (states) of the variable form, and the procedure yields a morphological type.
- Taxonomic classification is based on an ordered or hierarchical structure of categories that specifies inclusion relations. It is exemplified in pottery studies by the type-variety system.
- Taxonomic classification is sometimes more broadly defined simply as creating types, as opposed to analytic classification, which analyzes attributes to isolate and describe modes (Rouse 1960: 313–17).

The Tarahumara of Mexico call all pots *sekori* and distinguish three functional classes: pots to eat from, pots for parching corn, and small pots (called *sekori ranara,* the modifier being a term usually used to refer to one's children) (Pastron 1974: 103). At Manumanu, Papua New Guinea, vessels are given four names: *uro* or cooking pots, *hodu* water vessels, *nau* dishes, and *tohe* sago storage vessels (Groves 1960: 10). Differently named sizes of vessels often have different functions (e.g., Linares de Sapir 1969: 8). Among the Fulani in Cameroon, 84% of the classified pots in the households studied were "jars with short necks and everted rims . . . [that] come in five named sizes": *loonde* (or *ngiiramwal*, see below), *fayande gaari* (named for sorghum), *defruunde, hakoore* (named for a sauce), and a miniature *julduude* or ablution jar (in decreasing order; David and Hennig 1972: 8–12). Among the Kalinga in the Philippines, rice cooking vessels and vegetable/meat cooking vessels are differentiated lexically, although some of the size terms overlap; in other aspects of the folk classification there is clear differentiation of vessel types and names by both size and contents.

The Shipibo-Conibo, in contrast, name vessels by general shape categories, adding modifiers to denote size subsets, and though different sizes have different functions there seems to be little specificity in naming their intended contents. Cooking pots or ollas are called *kënti* and are distinguished by size as *ani* (large, used for beer), *anitami* (medium, used for meals), and *vacu* (small, for medicines). Similarly, jars (*chomo*) and beer mugs (*kënpo*) come in three sizes, but food bowls (*këncha*) and *shrania* exhibit less standardized size ranges (DeBoer and Lathrap 1979: 105–10).

Unsurprisingly, when any of these features such as size, use, or contents change, the vessel names may change too. For example, in Papua New Guinea, *uro* cooking pots and *tohe* water vessels are further distinguished lexically if the rims are accidentally

broken off (Groves 1960: 14n); among the Kalinga, if a rice or meat/vegetable cooking pot becomes worn out or cracked and is transferred to use in toasting, it ceases to be an *ittoyom* or an *oppaya* and instead is called a *linga.* Elsewhere, if the contents or use of an intact vessel varies, so does the name: the large olla-like Huichol pot called a *šáalei*^{h} is primarily used for brewing corn beer for ceremonial occasions, but if it is used for other purposes it may sometimes be referred to as a *kašuhéla*^{h} (= *cazuela*; a term often interchangeable with *šáalei*^{h}), whereas if it is used for water storage it becomes a *ya'é* (Weigand 1969: 16, 22). Among the Fulani, the largest storage vessel is called a *loonde* when it is used for water storage in a compound courtyard and *ngiiramwal* when it is used for dry storage within the hut (David and Hennig 1972: 8).

Ethnotaxonomies for pottery vessels are "emic" categorizations, as opposed to the "etic" categorizations used in scientific or devised classifications, and they are a traditional point of ethnographic research into pottery manufacture. Many investigators who have elicited vessel terminology express some dismay that such categories are so little evident to (or replicable by) outsiders, as in the comments about Kathmandu, above. The attributes that anthropologists and archaeologists commonly focus on—overall shape, rim and lip variations, base, surface decoration—may or may not covary significantly in native classifications (see, e.g., Weigand 1969: 13), and it is not always easy to penetrate their structure. In historical archaeology, similar use-based classifications are known from documents (e.g., probate inventories), which list vessels by name as well as by function, but many of these names—pipkin, for example—are no longer in modern vocabularies.

Although ethnospecific names for pottery vessels are of traditional anthropological interest, intensive studies of taxonomic systems of pottery are uncommon. Two studies examined the folk classification of vessels in highland Mexico from different perspectives. Their findings are important for understanding the nature of pottery classification among traditional societies, and the implications of these classifications are relevant to certain objectives of archaeological taxonomy (see also Miller 1985).

One study (Kempton 1981) addressed the problem of defining boundaries or disjunctions between categories, given the reality of continuous variation, through a model of "prototypes and graded extensions." This model holds that individuals identify categories of pottery both by prototypes, which can be considered typical or ideal examples of a particular object, such as a jar, and by extending the concept to other objects that are not "ideal" jars but still are "basically" jars (as opposed to being bowls, for example). Graded extensions reveal that within the attributes or dimensions by which a prototype is recognized, inevitable variations broaden the category beyond the ideal. This model was applied in Tlaxcala, Mexico, by eliciting classifications of drawings of variable pottery shapes (fig. 13.2). Although the informants' verbal definitions of vessel categories typically mentioned specific functions and the presence or absence of certain features (such as handles), their gestures and drawings stressed

shape, particularly width-to-height ratio (or "fatness") and neck position (Kempton 1981: 36, 39–40).

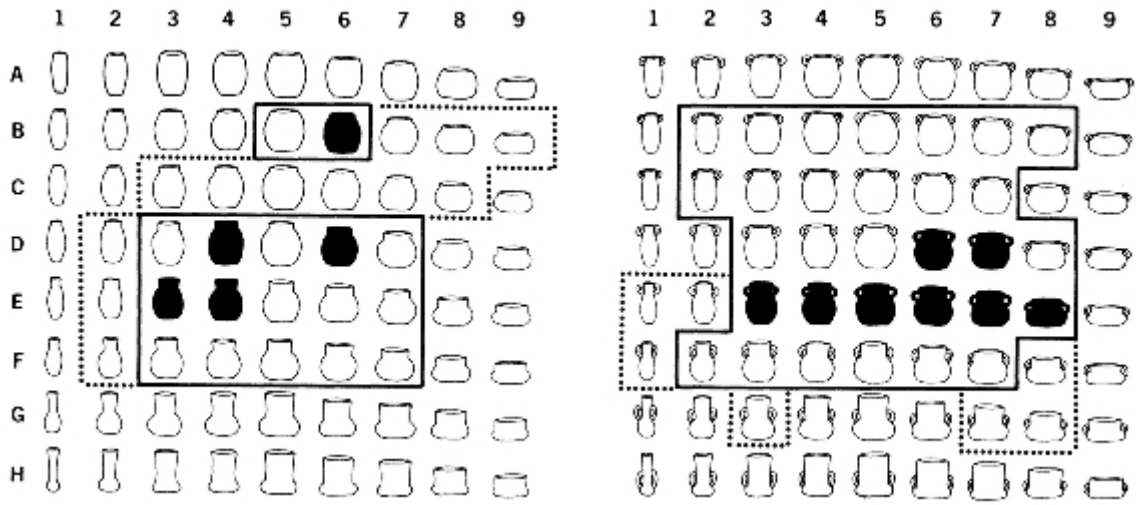

Figure 13.2 "Olla" as a vessel shape category identified by a young Mexican woman. Focal category members are solid colored; simple members are enclosed by a solid line; peripheral members are enclosed by a dotted line. After Kempton 1981: fig. 3.3.

Vessel definitions (both prototypes and extensions) varied with the age, sex, occupation, and socioeconomic status of the informant. For example, although males and females had generally the same prototypes, they extended these definitions in different ways. Males gave more weight (less extension) to shape, while females gave more weight to attachments such as handles, which are important functionally (Kempton 1981: 127). Similarly, although one might intuitively hypothesize that potters themselves would have more names for vessel categories or use more restricted category definitions, this did not appear to be so. Instead, like female informants, they gave more weight to function and attachments and less to overall shape in classifying the vessel drawings (Kempton 1981: 123, 138).

Another study of folk classifications of pottery was based on both attributes and ethnotaxonomies elicited from 85 potters and assistants in Puebla, Mexico (Kaplan and Levine 1981). Multivariate analyses revealed the structure of the taxonomy in part by creating a "cognitive map" of the features organizing cultural perceptions. A scaling plot based on the relative similarities of the twenty-five identified categories of pots in this study (fig. 13.3) revealed two primary features that differentiated them: restrictedness or nonrestrictedness of the form (axis I) and the absence or presence of single or multiple handles (axis II; Kaplan and Levine 1981: 876). Axis I parallels other binary oppositions within the pottery and in the culture itself. For example, the pots on the right side of the plot are associated with open forms; with red colors, black-on-red designs, or no decoration; and with life, daytime, heat, and femaleness. The left side of

the diagram is associated with closed forms, black colors or black-on-red decoration, and death, night, cold, and maleness.

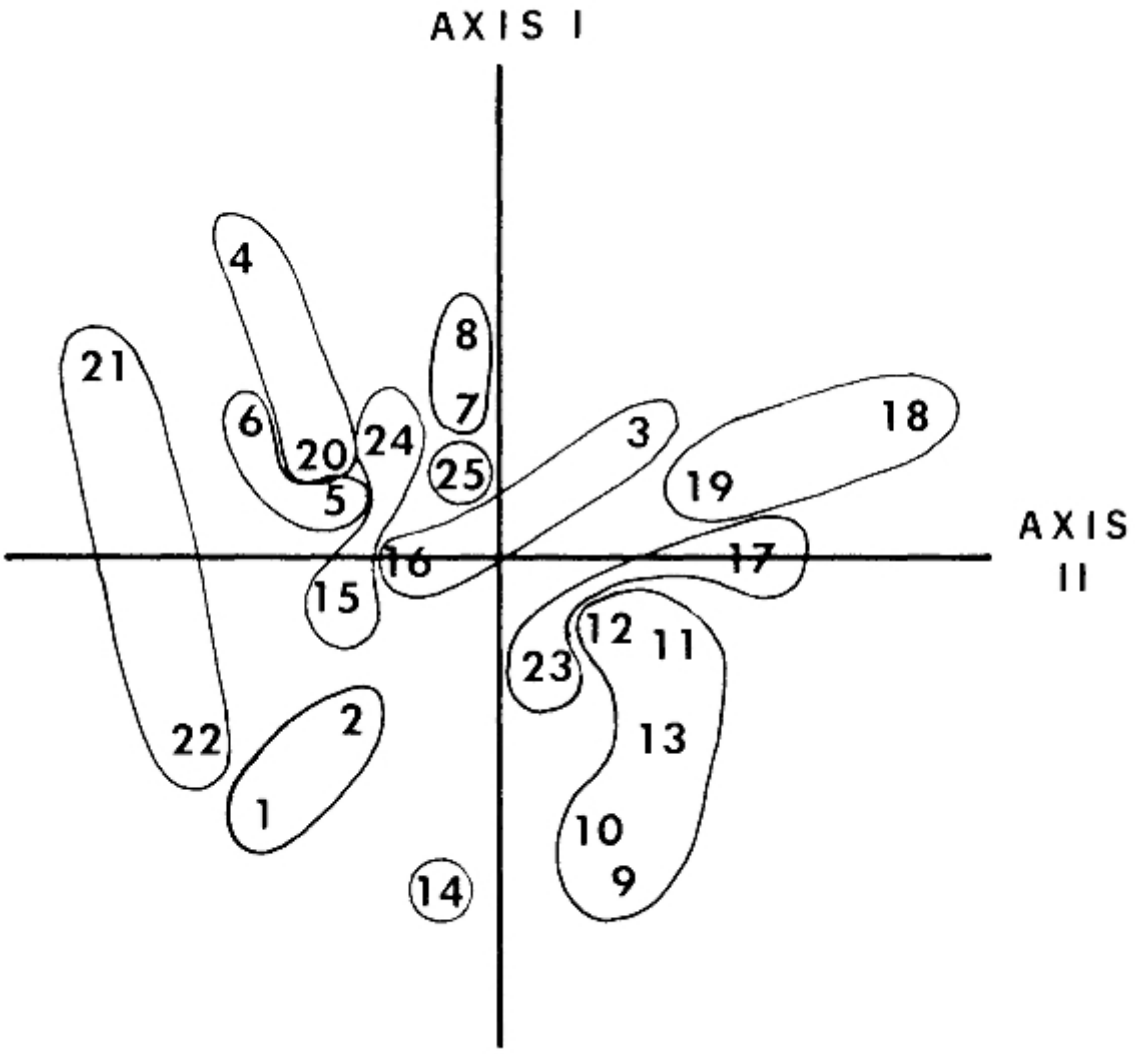

Figure 13.3 Multidimensional scaling plot of 94 features of 25 black-on-red glazed pottery types from Puebla, Mexico. The types are identified by number, and the groups obtained by cluster analysis are circled. The two major dimensions of scaling are open/closed forms (axis I) and multiple/nonmultiple handles (see text). After Kaplan and Levine 1981: fig. 3.

Ethnotaxonomies are, in other words, situation- or vessel-specific. They are, in the terms in figure 13.1, phenomenological (empirical, pragmatic) group identifiers based on use, rather than ideational (conceptual, analytical) classes based on abstract similarity relations.

13.4.2 Devised or Formal Classifications

The most typical approach to archaeological data is through devised, formal, or scientific classifications, which are created by the analyst. Although many schemes have

been developed for grouping similar entities in conjunction with varied archaeological objectives, these activities are comprehended by the more general purposes of classifications within all scientific disciplines. Formal classifications (Blashfield and Draguns 1976: 574; Gaul and Locarek-Junge 1999) structure the domains of disciplinary inquiry by

- organizing knowledge;
- furnishing a system for describing and naming the objects of study;
- fostering internal and external communication through shared terminology and nomenclature;
- permitting predictions about the relation of the classified items to other objects studied; and
- serving as extensions of and empirical justification for concepts used within the body of theory of that science.

Formal classification systems, whether by archaeologists, biologists, psychiatrists, or marketing researchers, are dependent on the analyst's selection of attributes, and may be described as monothetic or polythetic. Monothetic classifications are based on one or more attributes that are both necessary and sufficient for membership in a class; all members must possess these characteristic(s). Polythetic classifications, by contrast, are based on multiple attributes, no one of which is necessary or sufficient for membership. Individual members of the class must possess a subset of the attributes, but no single member of the class has to have all attributes. Thus members of polythetic sets or types are similar but not identical. Polythetic classifications are flexible and permit nesting or hierarchical ordering of subsets. Classification is not the final goal of any scientific field; rather, it is a fundamental structuring procedure by which disciplines organize their data.

A class known as "ware" has long been used informally in archaeological ceramic studies in the Southwestern United States and Mesoamerica, and wares seem to continue as the primary unit (rather than types) in Europe and the Classical area. Wares may be identified through a great range of attributes, including functional (e.g., kitchenware), decorative (black-figured ware), paste composition or textural (coarse ware), color (Fine Orange ware), surface treatment (glazed ware, Plumbate ware), form (beaker ware), firing technology (earthenware), period (Iron Age wares), and geographical location (Derbyshire wares). Although in these largely informal uses the members of named ware categories may share characteristics of color, firing, method of construction, temper, and so forth, their fundamental defining criteria are aspects of composition, manufacturing technology, or surface treatment. In the terminology discussed, these wares are generally monothetic paradigmatic classes and they correspond to procedural modes in analytical classifications.

Perhaps the most elaborate and widely used formal scheme for archaeological pottery classification, at least in North and Mesoamerica, is the type-variety system. Developed in the late 1950s as a systematic framework for creating, describing, and naming widely comparable historical-index classificatory units, the scheme began with the variety concept in the Southwestern United States. This was transferred to the

Southeast with elaboration of the type concept and synthesized into a "type-variety" system with sorting and naming procedures in application to Maya pottery (Gifford 1960; Phillips 1958; Rice 2013c; Smith et al. 1960; Wheat et al. 1958).

The polythetic type-variety system is a hierarchical procedure of classification in which varieties are the smallest unit recognized and are subsumed within types: for example, an incised type may have a groove-incised and a fine-incised variety. One or more types may be subsumed within a ceramic group (cf. Colton 1953), which is usually formed on the basis of similar surface treatments—for example, a red-slipped ceramic group—and may include different decorative types, such as incised, appliquéd, and polychrome painted. Groups are organized into wares. Elaboration of the type-variety approach and applications to Maya pottery (Aimers 2013; Gifford 1976; Willey et al. 1967) led to development of higher, more inclusive levels in this hierarchy, such as ware and system, and a concern with broader questions of integration and interpretation.

One of these higher-order units, ware, has evolved to incorporate technological variables such as surface treatment and paste composition. Surface-treatment attributes (presence or absence of a slip or glaze, its luster, color, etc.) are closely aligned with the attribute emphasis of traditional type-variety classification procedures, and thus they make it relatively easy to integrate wares into the hierarchy of units. Variables of paste composition (and manufacturing technology) are more difficult to place in this hierarchy, but they are also significant because they allow inferences about pottery production technique, organization, location, and trade distribution patterns—objectives that are aligned more closely with current archaeological methods and goals than with chronology-building (Rice 1976b, 2013d). Systematic incorporation of technological data into classification systems (e.g., through the ware concept) significantly extend classificatory procedures to incorporate paste composition and provenience information (see Rice 1982; Shepard 1976: 310–14). This is potentially a formidable task, chiefly because it is often difficult to interpret technological properties or identify composition without extensive laboratory analysis.

Statistically based pottery classifications were common in the 1970s and 1980s, but are currently little used except in conjunction with certain kinds of data, such as chemical composition. Cluster analysis (roughly, numerical taxonomy) was most commonly employed in such analyses. Cluster analysis is a set of multivariate statistical procedures for grouping entities by their similarity on a large number of attributes (Baxter 2003, 2009; Everitt et al. 2011; Kettenring 2006; Papageorgiou et al. 2001; Wishart 1999, 2006). The output is usually a treelike graph (a dendrogram; see fig. 17.6) showing successive linkages of similar entities. Factor or principal components analysis (e.g., Garson 2013; see also Christenson and Read 1977) is also used to extract major underlying dimensions of variability in the data, dimensions thought to be measured imperfectly and non-independently by the original attributes.

Verifying the quality of the classifications resulting from these mathematical procedures—that is, determining which is "best" for the data—is problematic. Choice of attributes and specific procedures is critical, for different classifications can result from different techniques. Although the methods replicate to some degree the archaeologist's polythetic artifact sorting (in which several attributes are considered simultaneously), they do not always accurately reproduce archaeological classifications of real data sets.

Much of the appeal of statistical approaches is that they offer solutions to the difficult and sometimes arbitrary procedure of drawing boundaries around classes—identifying discontinuities in what appear to be continuous variables. With qualitative variables it is easy enough, in principle, to determine classes. Color, for example, is a qualitative variable, and the boundaries between attribute states of black, white, and red pottery seem clear, as do categories of inclusions, such as limestone, shell, volcanic ash, and quartz sand. But subtle gradations of color and mixtures of inclusions result in overlapping categories, and continuous variables (size, diameter, thickness) give rise to other boundary issues, which force the classifier to make difficult decisions about lumping or splitting classes (Whitaker et al. 1998). Computer programs that permit hierarchical rankings of attributes (Whallon 1972) or accommodate mixed-level (qualitative and quantitative) data in groupings (Wishart 1999, 2006) are useful in this regard. The question is still, however, one of fuzzy boundaries: How much variability can exist within a class before it should be divided? The answer depends on the purpose of the classification and the variability in the data.

Although the statistical procedures used to identify types within these approaches to classification are themselves of considerable significance, what are more salient culturally are the interpretations of the types discovered. Traditionally, types have been viewed as intrinsically present in the data (a la Spaulding) and therefore as cultural realities constituting fundamental observations or "basic data." Argued to an extreme, however, this viewpoint can lead to the questionable interpretation of a particular classificatory scheme as the only possible one for the data and thus as the best and most meaningful one (Hill and Evans 1972: 235–38).

13.4.3 Form and Form-Based Categorizations

A popular alternative to devised or taxonomic classification is the creation of morphological types: classes of pottery based on form (and, by extension, inferred use). This is an exercise in attempting an emic classification, as well as in paradigmatic classification: creating equivalent units (e.g., bowl, jar, plate) on unordered dimensions (e.g., diameter, rim type, appendages). Technically, it could also be described as identification if the material of interest is assigned to already established classes (bowl, jar, etc.), or as categorization if not.

13.4.3.1 Size and Proportions

Classification of colonial-period vessels of the anglophone eastern United States (e.g., Beaudry et al. 1983) made the useful distinction between flatware (such as plates) and hollowware: those that enclose their contents by a restricted orifice. Absolute size or volume criteria are used to differentiate many of the categories. By this scheme a saucer can be distinguished from a plate and a dish by absolute diameter: a saucer is less than seven inches across, while a plate is seven to ten inches and a dish is greater than ten inches. Similarly, a cup can be differentiated from a drinking pot by volume: a cup has a capacity of less than a pint, while a drinking pot holds from one pint to two quarts. The local terms for, as well as the uses of, these vessels were known, a nicety rarely granted archaeologists working in areas lacking texts.

Box 13.2 Anatomy of a Pottery Container

Any ceramic vessel form can be described or characterized in a number of ways, often with explicit or implicit reference to particular shapes and their proportions in terms of human anatomy. Most simply, a vessel has three essential parts: body, base, and orifice (fig. 13.4*a*).

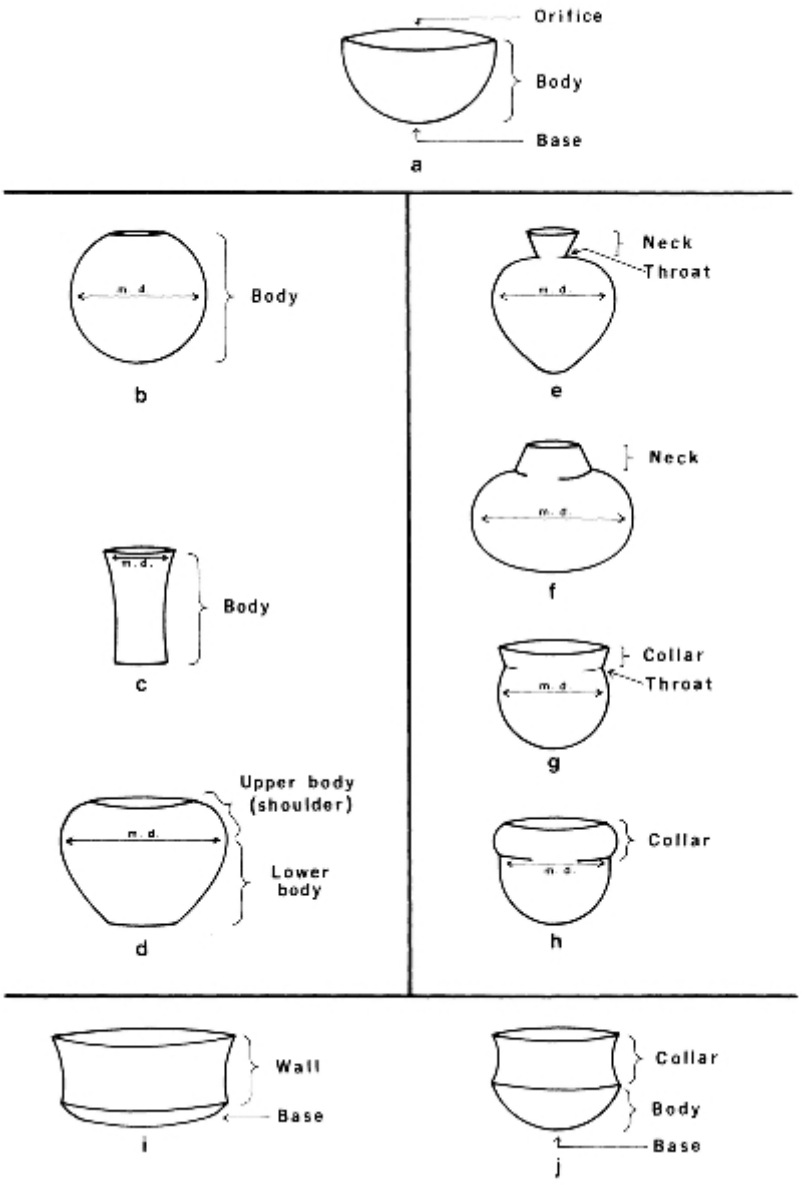

Figure 13.4 Major subdivisions of pottery vessel shapes: *a*, divisions of a simple vessel; *b–d*, vessel body; *e–h*, neck, collar, and throat; *i*, *j*, base and body on composite forms (m.d. = maximum diameter).

- The orifice or mouth is the primary opening of the vessel to the exterior.
- The base (or foot) is the underside of a vessel, touching the surface it rests on during normal use. Although this is self-evident for flat-based vessels (fig. 13.4*c,d*), for round-based vessels it may be difficult to determine when the base becomes the side. The juncture may be marked by a slight

change in curvature between the side walls and the underside, or a distinct angle may differentiate them (fig. 13.4*i*).

- The body (or belly) of a vessel is that portion between the base and orifice that includes the maximum diameter of the vessel or the region of greatest enclosed volume.
- The point of maximum diameter of the body may be called the shoulder.
- The area between the maximum diameter and the base is the lower body.
- If the mouth diameter is equal to or greater than the maximum diameter of the body (fig. 13.4*a,c*), it is described as an unrestricted orifice;
- If the mouth diameter is less than the maximum diameter, it is a restricted orifice. On a restricted form, the region between the maximum diameter and the orifice or neck is the shoulder or upper body of the vessel (fig. 13.4*d*).

The orifice may be subject to a great deal of elaboration, much of which is functional. The edge of the orifice is described by two terms, lip and rim (fig. 13.5), which are often used interchangeably because the point where one ends and the other begins is not always clear.

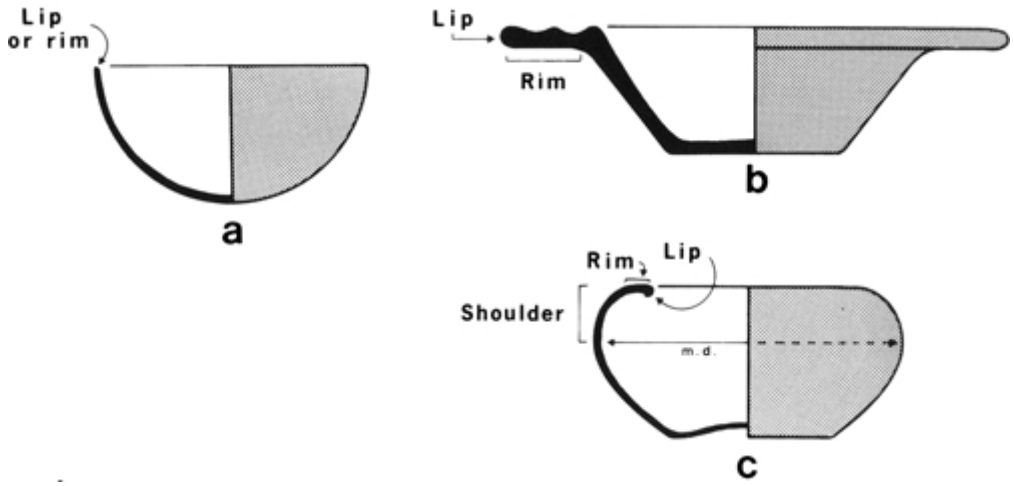

Figure 13.5 Lip and rim on various bowl and plate forms.

- The lip is the edge or margin of the mouth of the vessel; it may also be described as the edge of the rim of the vessel, meaning that the lip is part of the rim.
- The rim is easily distinguished only when it is articulated—set off by a curve or an angle from the wall or neck of the vessel (fig. 13.5*b,c*). Where such a change exists, the rim is the area between the change of orientation of the lip (the margin) and the side or neck of the vessel. A direct rim (e.g., figs. 13.4*a,c* and 13.5*a*), in contrast, has no change of orientation between the wall or neck and the lip, and the lip and rim are equivalent.
- The orifice may be raised and extended into a neck or collar.
- A neck is a restriction of the opening of the vessel (fig. 13.4*e,f*), beginning above the point of maximum diameter. Necks may join the body with a curve or an angle (see below).
- A collar usually begins at maximum diameter (or at a slight restriction close to it), and does not significantly reduce the orifice opening relative to the diameter of the body (fig. 13.4*g, h*). Collars typically join the body at an angle.
- Either the base of the neck or collar or its point of maximum restriction may be called the throat.

The three general vessel zones—orifice (including neck or collar), body, and base—may be elaborated, but because these modifications do not distort the primary shapes of the vessels or their proportions, they can be thought of as secondary form variations. They often have important utilitarian as well as decorative functions, however, and secondary does not imply insignificant.

Secondary form or shape attributes includes appendages and flanges or ridges.

- Appendages are primarily of three kinds: supports (or feet) attached to the base; handles placed on the body, neck, or collar; and spouts applied to the orifice, neck, collar, or body.
- Flanges and ridges are bands or projections that extend out from the vessel wall (see fig. 22.1), differing in degree of projection (flanges are greater than ridges). They are usually added to the wall of a fully shaped vessel rather than being part of the wall and its contours, and most typically (though by no means always) they run around the circumference.

Each of the primary and secondary anatomical zones or features described above may be further identified by terms that describe its appearance or its relation to other features. In other words, each of these zones or features may be considered an attribute or variable of a vessel and described more specifically in terms of the possible states or conditions in which it may appear (see, e.g., Redman 1978a: fig. 8.6). Particular kinds of rims or bases or flanges—not simply their presence or absence—may be of functional, stylistic, chronological, and social/ethnic significance in distinguishing the makers and users of different kinds of ceramic vessels. Because the variations of orifices and rims are usually given chronological and cultural significance, archaeological ceramic reports typically devote a great deal of space to illustrations of vessels in cross section, called profiles (e.g., fig. 13.5*a*–*c*).

Use-related classifications of vessel shapes by anthropologists and archaeologists are most frequently based on proportions: ratios of height to maximum diameter, and kind or size of orifice (e.g., Henrickson and McDonald 1983: 631–36; Kempton 1981: 46; Longacre 1981: 54; Millett 1979a: 37). The height of a vessel includes the body plus a neck or collar if present, but usually does not include basal supports. The diameter is the maximum diameter of either the body or the orifice (in an unrestricted form), excluding appendages such as handles, spouts, or supports.

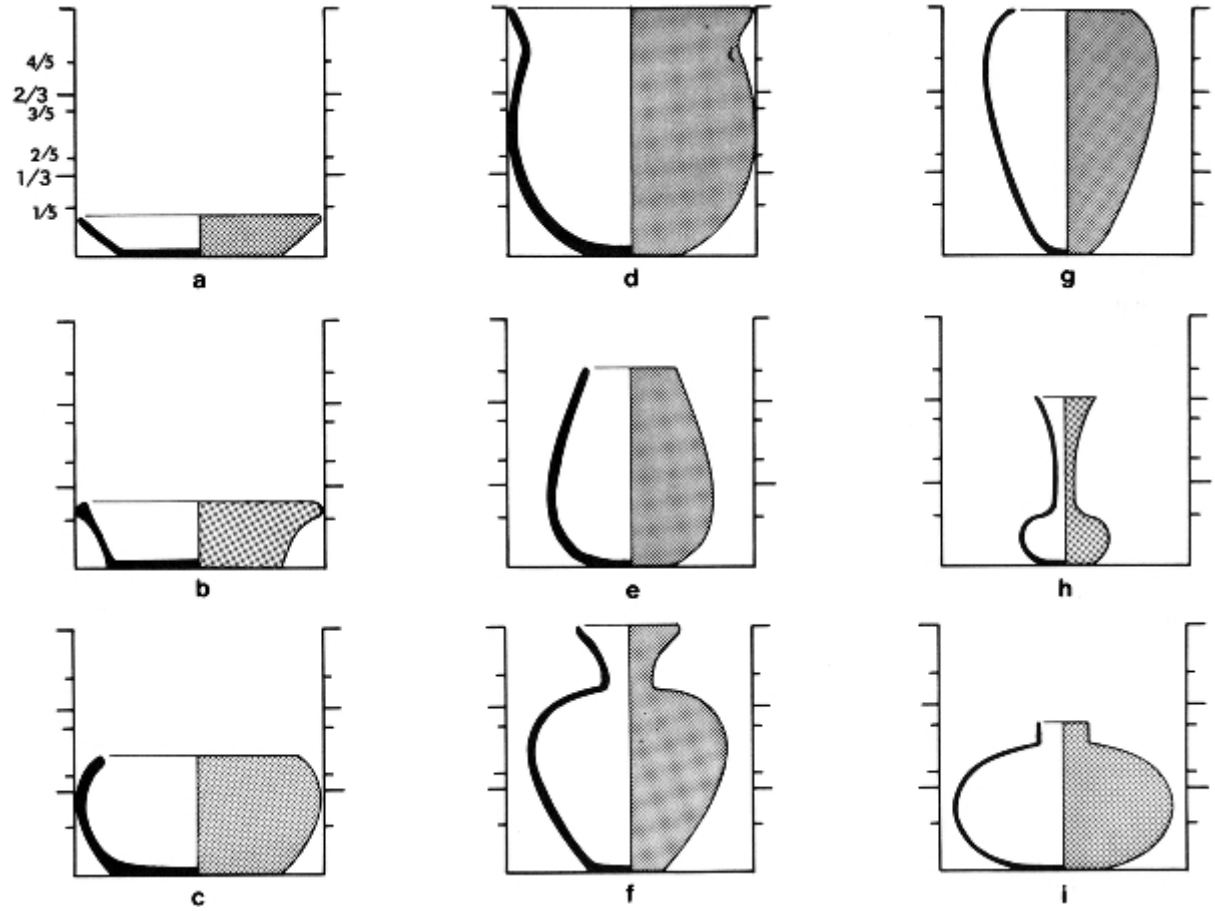

Figure 13.6 Vessel proportions (as ratio of height to diameter) and shape categories: *a*, plate; *b*, dish; *c*, bowl; *d*, bowl; *e*, vase; *f*, jar; *g*, neckless jar with diameter approximately 70% of height, which could be classed as a vase; *h*, *florero*, with a restricted orifice, which could be classed as a jar; *i*, jar with height 66% of diameter, which would be classed as a bowl but for the neck.

One classificatory scheme for Maya pottery included five vessel forms: plate, dish, bowl, jar, and vase (Sabloff 1975: 23; Smith 1955). Plates and dishes are shallow forms with unrestricted orifices: a plate (fig. 13.6*a*) has a height less than one-fifth its maximum diameter, whereas a dish (fig. 13.6*b*) is slightly deeper, with a height more than one-fifth but less than one-third of its maximum diameter. A bowl (fig. 13.6*c, d*) may have a restricted or an unrestricted orifice and its height varies from one-third to equal to the maximum diameter. Bowls may have collars but they do not have necks. A jar (fig. 13.6*f*) in this scheme is a necked (and therefore restricted) vessel with its height greater than its maximum diameter (see also Shepard 1976: fig. 21*k–q*).

The shape category "jar," in particular, varies widely from culture to culture in both proportion and secondary form attributes, and provides another illustration of the use of graded extensions. A common large jar form in the Southeastern United States (fig. 13.6*g*), for example, would not be a jar in the Maya scheme above because it has no neck. Similarly, a jar form in the Southwestern United States (fig. 13.6*i*) would be a bowl (its height is more than one-third the maximum diameter) but it has a neck. If jars must have necks, then there can be no neckless jars (sometimes called seed jars, or *tecomates* in Spanish), however, and what are the vessels in figures 13.6*g* and *e*?

A review of classification issues, informed by ethnographic and ethnohistorical data on Zulu ceramic containers and applied to archaeological problems, emphasized the importance of considering together size (height) and capacity (using width as a proxy; Fowler 2006: 106–9). A graph of these two variables showed that "the quantitative, etic distinctions mirror the qualitative, emic divisions," and these attributes of form "relate directly" to the key use-related properties of capacity, mobility, and the accessibility of liquid contents (Fowler 2006: 108, 113).

13.4.3.2 Special Shape Terms

Several attempts have been made to standardize and clarify vessel-shape terminology (e.g., Fournier 1981), often with concordances of terms in English, Spanish, and French (Balfet et al. 1983; Castillo Tejero and Litvak 1968; Theuvenin et al. 1970). Certain vessel category names seem to be virtually universal—at least among anglophone archaeologists—but though they have important functional implications, their definitions are remarkably imprecise.

At first glance it seems desirable to have some agreement and standardization of form terminology, particularly for the almost universal but still ill-defined categories of jar and also bowl. But specialized or local shapes occur virtually everywhere and often have unusual features of proportion, size, or appendages. A juglet or a canteen. An *aryballos*, *florero*, *pithos*, *krater*, and *mortarium*, used in South America, Mexico, the Near East, Greece, and Britain, respectively. Many non-English terms for shape or use have entered the English-speaking literature on pottery and modern culinary ware, such as olla, tagine, and cocotte. Though these local terms are specific and precise, they may not convey any information to an audience outside those immediate areas. There is no reason these regional vessel form classes should be forced into attempts to create a standard or universal scheme of vessel categorization.

And problems remain in English categorizations. Consider the terms basin, mug, bottle, jug, vase, flagon, and beaker. Taking the last three of these, a vase (fig. 13.6*e*) is a restricted or unrestricted vessel with a height greater than its maximum diameter. Vases may or may not have restricted orifices, but their heights must be greater than their diameters. Can vases have necks? If they cannot, then figure 13.6*h* (a *florero*) is not a vase; if they can, then how might necked vases be differentiated from necked jars? Useful alternative terms are flagon, "a vessel with a neck very narrow in comparison with its height and girth," and beaker, "a vessel whose height is greater than its rim diameter; and which is of suitable size and shape for drinking from" (Millett 1979a: 37). But a scattergram of the relation between height and rim diameter in 250 complete Romano-British vessels showed that flagons, jars, dishes, and bowls could be easily separated, but beakers could not be clearly differentiated from jars (Millett 1979a: 37, fig. 12).

Box 13.3 Reconstructing Form from Sherds

Archaeologists face an additional problem in studying the function of pottery containers recovered from their excavations: most are broken and incomplete rather than whole pots. If whole vessels were smashed in place either at the time of deposition or shortly thereafter, the pieces can usually be glued back together and for study purposes the vessel is as good as new (or better, because the fractured edges allow examination of paste variables). Too often, however, the pottery remains are incomplete fragments, and it may or may not be possible to determine the form of the original pot.

Rim sherds provide the most information for assessing the size and shape of a vessel. By fitting the curve of a rim sherd to a standard diameter-measurement template, typically marked off in centimeter units, one can calculate the orifice diameter (fig. 13.7). Care must be taken to ensure that the lip of the sherd forms a plane matching that of the orifice of the original vessel and that these both correspond to the plane of the rim-diameter chart (see Joukowsky 1980: 423).

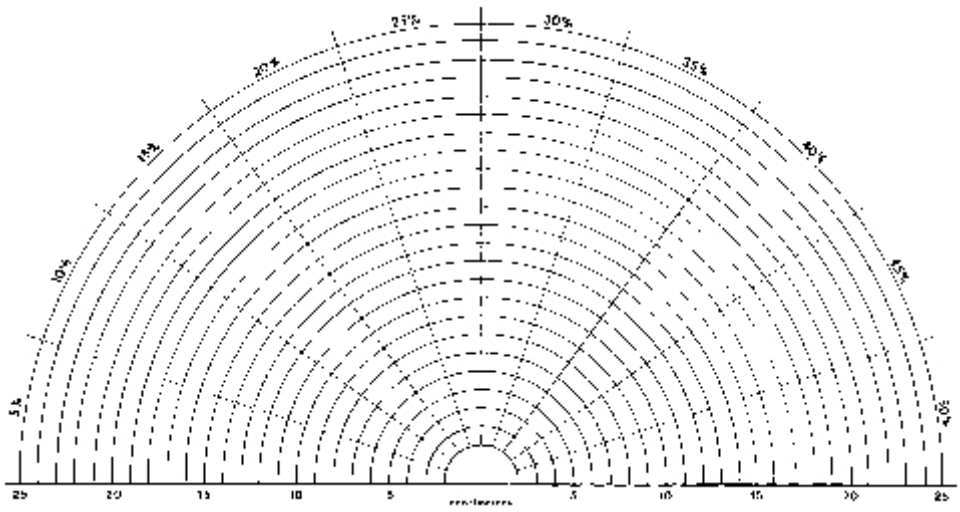

Figure 13.7 Template for measuring the orifice radius and diameter of a rim sherd and estimating (in 5% intervals) the percentage of the total circumference present.

The easiest way to do this is to hold the sherd so the lip is at eye level. A horizontal plane can be envisioned by tilting the sherd until three points along the uppermost edge—one at each end of the sherd and one in the middle—are aligned horizontally. At the same time, the angle of the wall or neck against the vertical can be determined and, if the template has been appropriately marked, the percentage of the total rim circumference can be estimated. These procedures establish the mouth diameter and wall orientation of the vessel; depending on the size of the sherd, they may also establish vessel height and maximum diameter. The base form or diameter cannot be determined unless the vessel fragment includes part of the base.

A common problem in this procedure arises from asymmetry: the rim may be uneven either vertically or horizontally, making it difficult to establish the precise orientation and diameter of the sherd. In addition, there may be considerable difference in diameter estimates from individual to individual (see DeBoer 1980), and an alternative procedure using a curve-measuring device similar to a lens gauge has been proposed (Plog 1985).

Base sherds are often less informative than rim sherds (cf. Frankin 1971); they provide evidence of the type of base used, and perhaps its diameter, as well as the orientation of the wall to the base. As with rim sherds, further information on vessel height or maximum diameter depends on the size of the

sherd. Base sherds may be more accurate than rims in classifying general shape categories (Froese 1985: 239).

Body sherds are, on the whole, the most difficult to work with. This is unfortunate, because most archaeological ceramic collections consist primarily of body sherds; for most vessels, far more sherds result from breakage of the body, which has a greater surface area, than from the proportionately smaller rim and base regions. Very often it is extremely hard to determine whether the sherd came from the top or bottom of the body, much less suggest the vessel's size and shape. This problem may be lessened if flanges, ridges, decoration orientations, handles, or other appendages occur on the sherds. Sometimes there are other indications of the sherd's location and orientation: marks of surface treatment (scraping, burnishing), drips of paint, smooth breaks from coil fractures, or finger ridges (rilling) from throwing.

If the body sherd can be oriented to vertical and horizontal planes by these procedures, some idea of its position on the vessel can be gleaned. With vessels that are approximately spherical, the radius and circumference can be estimated from a sherd (see Greer 1977; Landon 1959) by measuring the chord (the straight line between the ends of the interior curvature of the sherd) in the horizontal plane (fig. 13.8). First the radius is calculated using the formula: $r = (y^2 + x^2)/2x$. Here, y is half the length of the chord, x is the depth or height from the chord line to the concave interior surface (a segment of the radius), and r is the unknown radius of the circle. The value of r is then substituted in the formula for the circumference of a circle: $C = 2\pi r$.

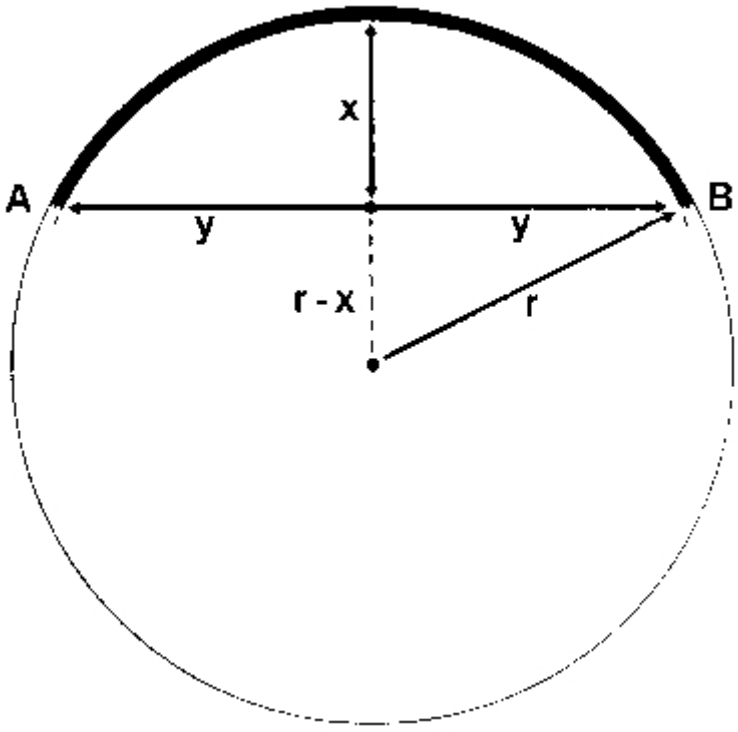

Figure 13.8 Formula for calculating radius and circumference from a chord; r = radius (unknown); y = half length of chord (or $AB/2$); x = height from chord to interior surface. Where only body sherds are available for calculating vessel diameters or circumference, the measurements available and desired are those of a right triangle whose sides are y, r, and $r–x$. By the Pythagorean theorem, the square of the hypotenuse of a right triangle (r) is equal to the sum of the squares of its other sides (y and $r–x$). This equation can be solved for r using $r = (y^2 + x^2)/2x$, with the calculated value then substituted in the formula for calculating the circumference of a circle ($C = 2\pi r$).

The figure that results from these computations is the circumference of the vessel in a horizontal plane that cuts its body in the region represented by the broken fragment. This is not necessarily the maximum diameter of the pot unless it can be determined that the sherd came from its widest portion and the proper orientation of the sherd can be ascertained. Estimates of vertical dimensions (e.g., height of the pot) cannot be made using the formula for the circumference of a circle unless it can be determined that the vessel was spherical.

13.4.3.3 Geometric Forms and Contours

Other approaches to classifying vessel shapes are based on volume with reference to geometric shapes: three solids (sphere, ellipsoid, and ovaloid) and three surfaces (cylinder, cone, and hyperboloid). Surfaces have no defined end points or dimensions (fig. 13.9). These shape classes may be used for restricted or unrestricted vessel forms; the orifices of any of these forms may have a neck or collar added, which is itself a section of a geometric form. Thus not only simple but also composite and complex vessel shapes can be described by their geometric equivalents.

The hyperboloid gives rise to vessel or neck contours that curve inward or outward, while out- or in-slanting walls represent sections of cones. Cylinders are always unrestricted forms. Spherical forms are often called globular, especially jar bodies. The ovaloid is the closest approximation to forms sometimes described as pyriform or pear shaped. The low ellipsoid form—the ellipsoid with its long axis in the horizontal plane—is usually thought of as having greater width than a sphere, but a cross-sectional cut through such a vessel at its maximum diameter would yield a circle, not an ellipse. With low, unrestricted bowl or dish forms, it is often difficult to determine which of the convex forms is represented: sphere, oval, or ellipse. In such cases it may be clearer simply to label the form semispherical or subspherical than to specify a particular geometric solid.

The analogies between vessel shapes and geometric solids or surfaces provide a basis for describing vessel forms. One such scheme assigns numerical values to the basic silhouette and to reference points on the silhouettes (fig. 13.10). For example, a round-sided bowl with a flat base would be coded 1:1–3 by this scheme. Most vessel forms can be described as sections or combinations of these geometric forms (plus a rectangular solid and minus the ovaloid). Three-dimensional imaging techniques and computerized "geometric morphometrics" are likely to become more popular as a means of characterizing the shapes of large collections of vessels (e.g., Wilczek et al. 2014).

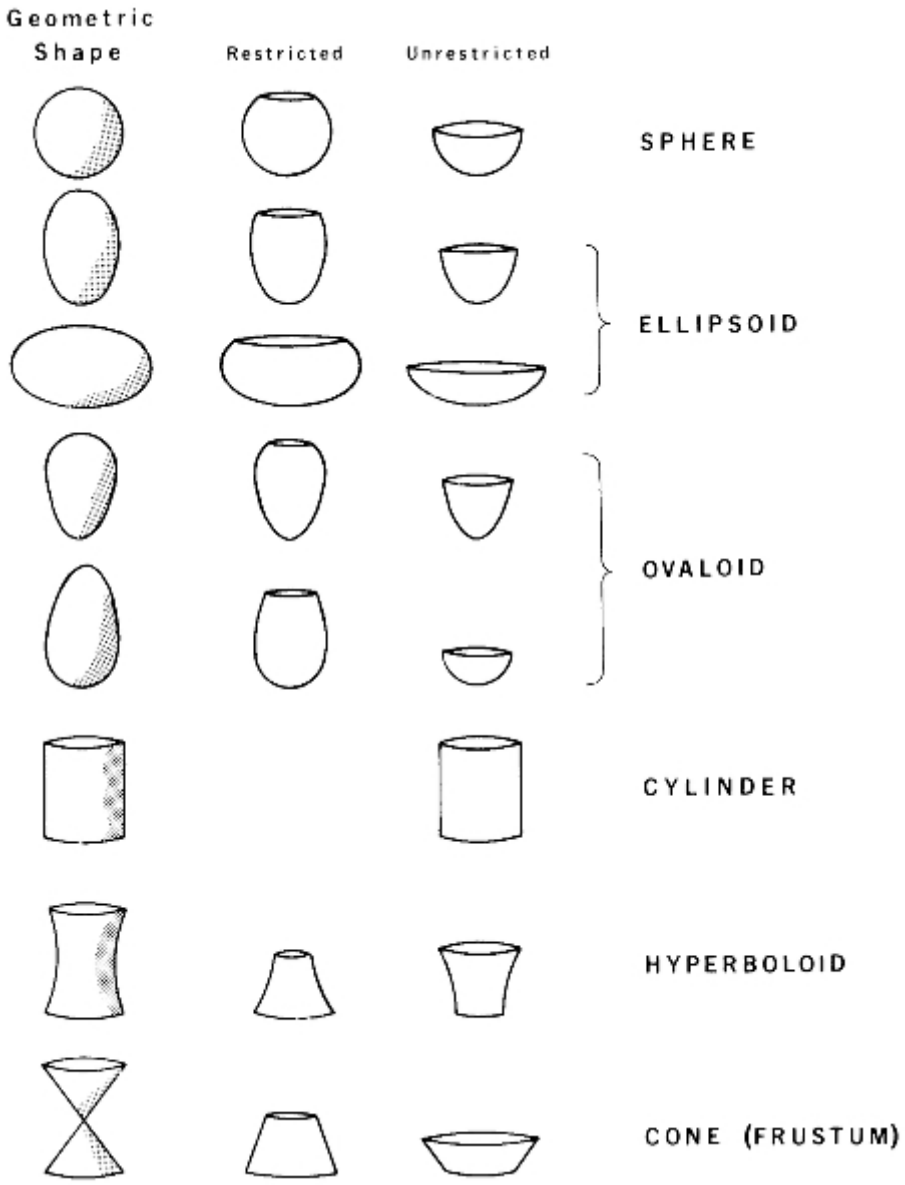

Figure 13.9 Geometric solids and surfaces as references for vessel shape description; sections of these shapes may combine with sections of other shapes to form necks, collars, or bases of composite or complex vessel forms. After Shepard 1976, figs. 23 and 24.

Consideration of vessel shapes as geometric solids permits calculations of vessel volumes or capacities by inserting various measurements into standard formulae (table 13.1), although there are problems with most methods (see Rodriguez and Hastorf 2013). One method for calculating the capacity of irregular shapes and incomplete vessels is the "summed cylinders" method. The interior of the vessel, or of a profile drawing of it, is envisioned as divided horizontally into a series of equal, narrow slices stacked one on top of another from bottom to top (fig. 13.11). These slices are a series of thin cylinders, the volume of which can be calculated by formula and then summed to arrive at the total volume of the vessel in cubic centimeters or cubic inches.

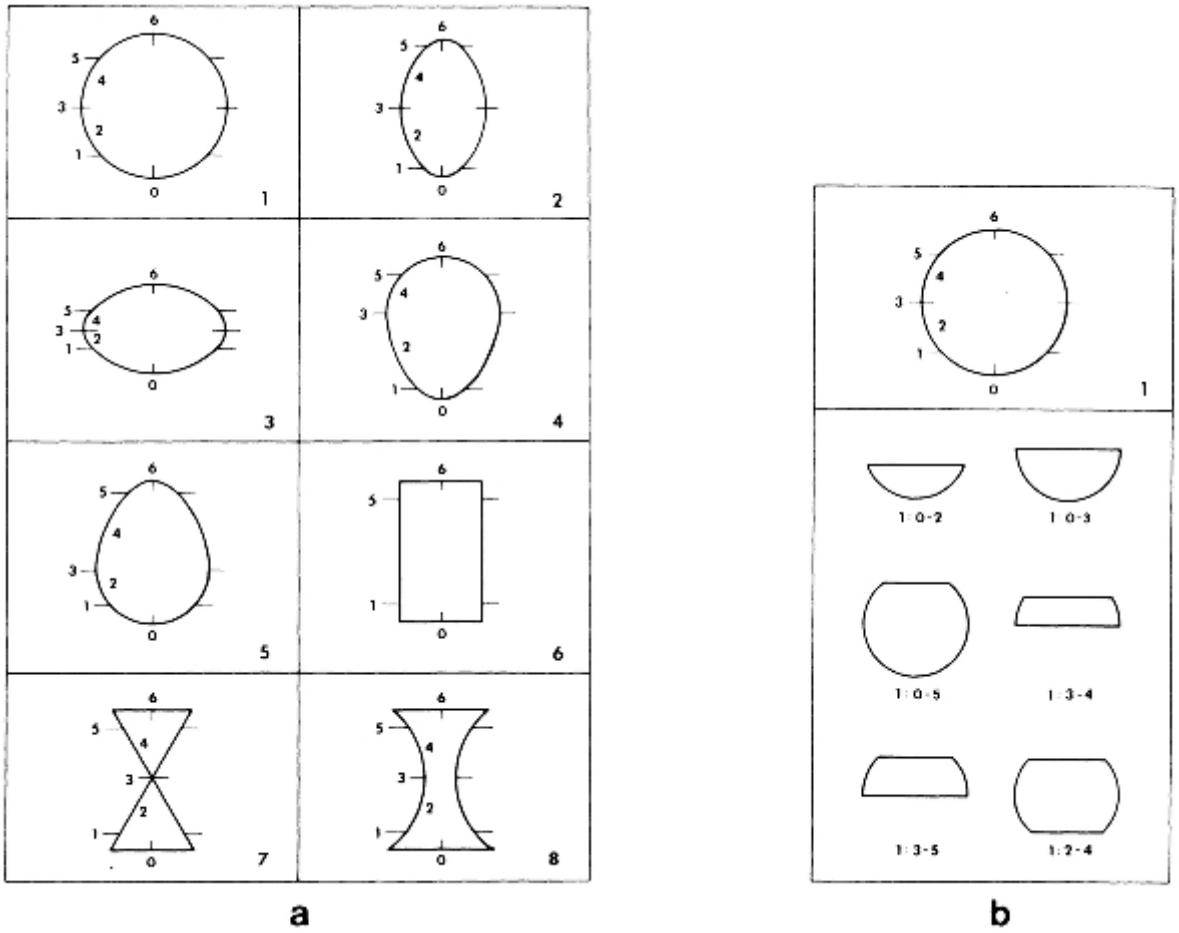

Figure 13.10 Reference points and line segments for describing vessel shapes: *a*, different basic shapes; *b*, vessel shapes described by segments of a circle. After Castillo Tejero and Litvak 1968: 12, 15.

A similar system of shape classification is based on vessel contours and eschews quasi-functional terms such as jar and bowl (Shepard 1976: 225–36). Shapes are differentiated by "characteristic points" of curvature or angling of the vessel contour; structural terms, principally orifice characteristics; and reference to geometric solids and surfaces. These classificatory organizations can be either used separately or combined into a single construct. Four "characteristic points" determine the contours of a vessel silhouette or vertical section (fig. 13.12; Shepard 1976: 226).

- End points (fig. 13.12*a,b*) are at the top and bottom of the silhouette, at the mouth and base.
- Tangent points mark where the tangent of curvature of body or neck or both is vertical.
- A corner point (fig. 13.12*c,f*) is an abrupt change in the orientation of a vessel wall, or an angle in the joining of vessel parts such as neck and body. The join of wall to base acts as a corner point only if the base rises to join the body; otherwise it is simply an end point.
- An inflection point marks the change of direction of curvature of two parts of the vessel (fig. 13.12*d*); it lies between two points of vertical tangency.

Table 13.1 Formulas for Calculating Volumes of Geometric Shapes

Sphere	$V_S = 4/3\pi r^3$
Hemisphere	$V_H = 2/3r^3$
Spherical segment	$V_{SS} = \pi r^2(r - h/3)$
Ellipse	$V_e = 4/3\pi abc$
Cylinder	$V_c = \pi r^2 h$
Cone	$V_k = (\pi r^2 h)/3$
Frustum	$\pi h/3(r^2_1 + r_1 r_2 + r^2_2)$

Note: r = radius
r_1 = radius of base
r_2 = radius of truncation
h = height
a = vertical axis
b = larger horizontal axis
c = smaller horizontal axis
π = 3.141

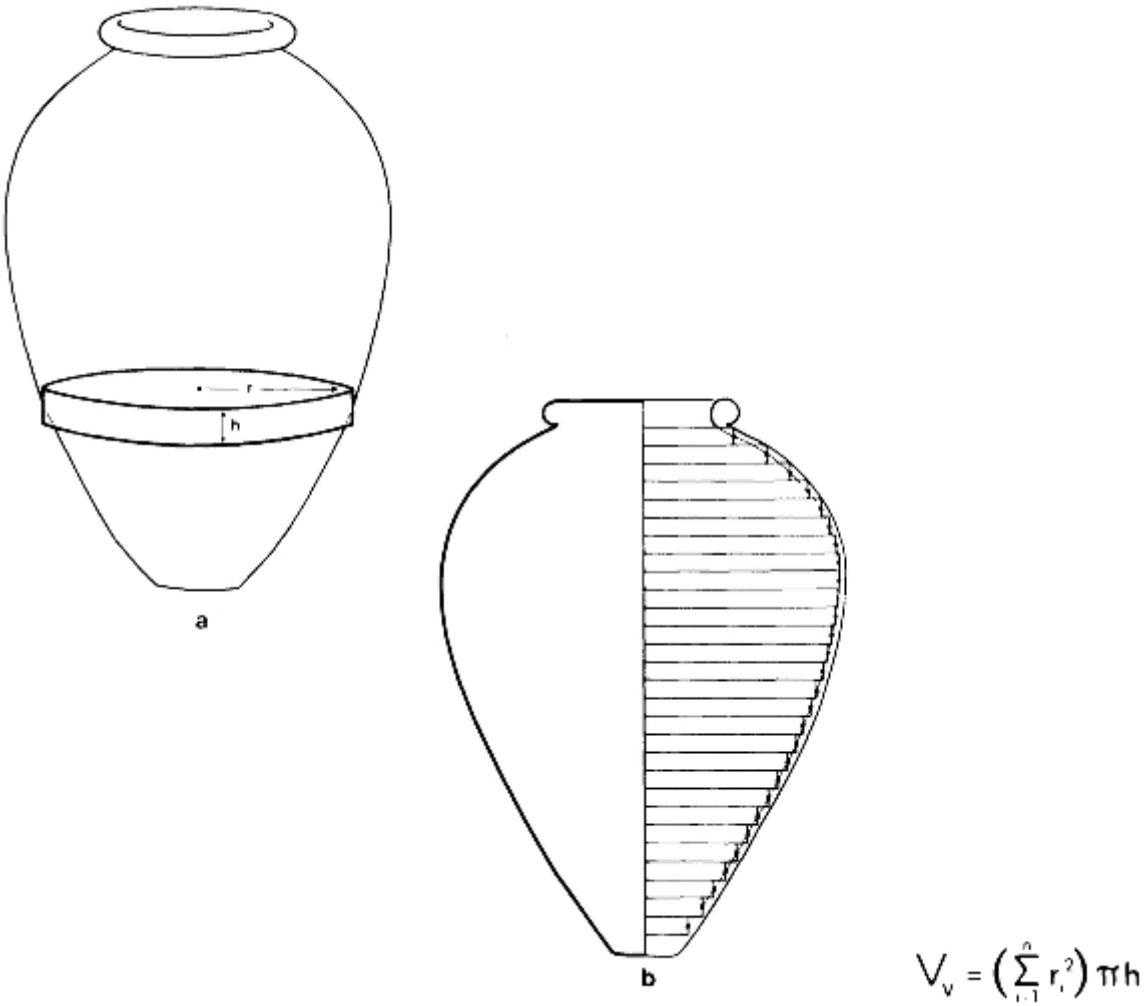

Figure 13.11 The "summed cylinders" method of estimating the volume of a vessel. The vessel is divided into a series of equal horizontal slices or thin cylinders, the volume of each cylinder is calculated ($\pi r^2 h$), and these are summed to give an estimate of the total volume of the vessel.

Corner and inflection points provide a basis for the structural classification of vessel contours as simple, composite, inflected, and complex (Shepard 1976: 231–32). Vessels with simple contours or silhouettes have a smooth, uninterrupted straight or curving wall; they lack angle and inflection points (fig. 13.12*b*,*e*). Composite silhouette vessels have a single corner point (fig. 13.12*a*,*c*,*f*), and inflected vessels have a single inflection point (fig. 13.12*d*). Complex-contoured vessels have two or more corner points or inflection points or one or more of each (fig. 13.12*g*). Bowls may fall in any of these categories. Necked vessels cannot be simple; they are either composite, inflected, or complex, while collared vessels may be composite or complex.

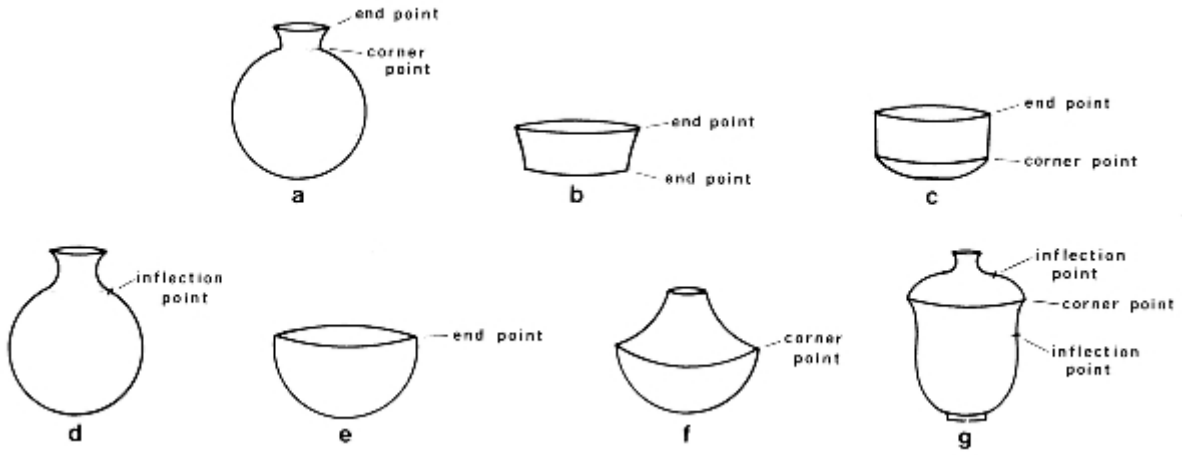

Figure 13.12 Characteristic points of a vessel profile.

13.5 Why Classify Pottery?

Most archaeological pottery typologies are devised classifications. Devised classifications are scientific tools that, in the case of pottery, were elaborated to standardize descriptions of artifacts, develop chronologies, and assist with intersite comparisons. These descriptive and space-time organizational goals have largely been met, although to varying degrees in varying culture areas within the discipline. In addition, with the development of new methods and approaches in archaeology—chronometric dating, compositional analysis, ethnoarchaeology—and new theoretical orientations, the field's objectives have changed substantially in the early twenty-first century. Archaeological pottery research in general has benefited extensively from these developments, but classificatory systems have not kept pace. The procedures still in use today are by and large the ones devised long ago for chronology building. Thus, the advice of J. O. Brew in 1946 still stands: we would benefit from new classificatory systems, procedures, or categories to address particular morphological/functional, technological, and stylistic issues.

Some of the problems in the literature on archaeological and ceramic classification are endemic among classifications in general. One example concerns boundaries: all classifications, by definition, require putting objects into one category or another. Any artificiality in archaeological classifications arises not from the nature of the type concept itself or from the need to impose boundaries, but from the conflation of decisions made by the analyst. These decisions are shaped not only by the requirement of selecting a limited number of attributes for the classification, but also by uncertainty about whether the excavated collection (a sample) represents the full range of pottery at the site (the population), adequately and without bias. In addition, types focus on attribute norms within the collection, but variations—such as might be caused by changes in uses or aesthetic desiderata through time, or by new manufacturing techniques—are rarely incorporated systematically (although the use of varieties in the type-variety system has this potential).

In addition, although whole artifacts function simultaneously in many different realms during their active use-lives, individual attributes (or states) may be more narrowly directed. Thus different sets of attributes will be more or less informative depending on the anthropological question or problem under investigation. Types based on primarily functional, morphological, or technological variables will crosscut standard devised or folk classifications but still represent valid associations of attributes.

A thread running through the literature on archaeological classification has been an aspiration to replicate, or a concern about reconciling, devised (artificial, etic) classifications with folk categorizations purportedly inherent to and discoverable in the data. In North America, at least, a key interpretation grounded in the types-are-discovered position was that types were "real" and therefore reflect the ideas and

values of the ancient people who made and used the artifacts. Types, therefore, should reproduce the artisan's ideas underlying the products (e.g., Deetz 1967: 45–46; Krieger 1944: 278). The importance of this issue in early typological debates led to considerable efforts to cloak devised classifications in folk (emic) clothing.

But ethnotaxonomic studies call into question whether this objective is feasible, or even desirable. These investigations illustrate that folk classifications are typically too fluid and context-based to be accommodated within the constraints of archaeological data recovery and inference systems. Pots are categorized by their users by size, age, contents, function, and location of use—the kinds of information the archaeologist is unlikely to have. In addition, societal heterogeneity is reflected in the heterogeneity of its categorizations; pottery vessels may be classified (named) differently depending on the age, sex, status, and occupation of the classifier. Overall shape may be less important to folk classification than vessel proportions, size, intended contents, or particular features of secondary shape variation that have functional significance, such as spouts or handles. Besides these issues, the question of verification is also relevant: how can archaeologists verify whether the devised categories correspond to native categorizations? In sum, although it is certainly not *un*desirable to achieve some correspondence between devised and folk classifications of archaeological pottery (Fowler 2006), this should not be the only criterion for assessing the overall utility of a classificatory system.

14 Characterization

> The immediate purposes of a ceramic technological investigation are to identify the materials and locate their sources, to study the indications of workmanship, and to describe properties by reference to exact, impersonal standards.
>
> Shepard 1936: 389

The analysis of formed and fired ceramic materials—whether ancient or modern, whole or in fragments—usually begins with characterization: a description of the object and its properties. In modern industry, with its advanced ceramics and composites, characterization refers to the qualitative and quantitative description of these materials' composition and structure; the procedures are carried out for research and development, reproducibility, quality control, and maintenance of performance standards (Hench 1971: 1; Loehman 2006). In archaeological studies other objectives are at the fore, and a large battery of analytical techniques and instrumentation is directed toward identifying how the ceramic might have been used in the past and inferring the location, resources, and techniques involved in manufacture. Thus the characteristics analyzed include color (chap. 16), composition (chap. 17), and mechanical and thermal properties such as hardness, strength, porosity, and resistance to thermal stresses (chaps. 18 and 19). This chapter provides an introduction to the historical background, objectives, and concepts of ceramic characterization, with an emphasis on selecting appropriate samples.

14.1 Historical Background

Characterization studies apply the concepts and techniques of the natural, physical, and materials sciences and engineering to archaeological and ethnographic objects. With respect to archaeological data, these approaches are part of the broader subfield of multidisciplinary research known as archaeological science or archaeometry: application of the methods of physics, chemistry, and materials engineering to artifactual data—not only ceramics, but also stone, metal, and glass.

The use of physical and materials science techniques to study archaeological artifacts can be traced back to the late eighteenth century. Although the earliest investigations of the chemical composition of ancient artifacts were typically directed toward metals, a few focused on glass and pottery, especially in the Classical area. Nineteenth-century chemical analyses of ceramics addressed the composition of the pottery of Nineveh (Layard 1853) and Athens (Richards 1895), and of Roman glazes (see Meschel 1978: 7). Mineralogical investigations of ancient pottery with petrographic thin-sections also began in the late nineteenth century (Bamps 1883; Nordenskiöld 1893), with Anatole Bamps reporting that red and black colored layers in cross sections of individual vessels represented degrees of oxidation in firing rather than different clays. Gustav Nordenskiöld analyzed sherds from Mesa Verde (Colorado) along with local clays and tempering materials.

The first half of the twentieth century saw the founding of modern ceramic technological studies. Significant contributions during this period include investigation of the chemical composition of black pigments in pottery of the Southwestern United States (Hawley 1929, 1930); the extensive technological, chemical, and petrographic studies of Anna O. Shepard at Pecos (1936), the La Plata District (1939), and the Rio Grande valley (1942a) in the Southwestern United States and at San Jose, British Honduras (1942b), and Kaminaljuyú, Guatemala (1946), in Mesoamerica; the technological studies of Frederick R. Matson at Seleucia on the Tigris in the Near East (1939) and at the Younge site in Michigan (1937); use of petrography at Troy (Felts 1942) and in Haiti (Horton and Berman 1941); early application of heavy mineral analysis in England (Wallis and Evens 1934); and spectrographic studies of early Chinese and Egyptian glass (Farnsworth and Ritchie 1938; Ritchie 1937).

Also during this period, several analytical instruments were developed that came to be of great significance in ceramic and other artifact studies. Electron microscopes were invented in the 1930s and X-rays came to be a reliable tool for investigating mineral structures. X-ray diffraction analysis revealed that clays were crystalline substances, stimulating a flood of studies identifying clay minerals and their properties (chapters in Part 2), and X-ray radiography showed early promise as an investigative technique in archaeology (Drier 1939; Titterington 1933).

These decades also saw efforts to standardize the methods of analysis and descriptions of archaeological pottery, such as Benjamin March's *Standards of pottery description* (1934). Indeed, Shepard's "The technology of Pecos pottery" (1936) can be seen as constituting a first draft of her later *Ceramics for the archaeologist*, first published in 1956 and republished at least eleven times. In 1928 Carl E. Guthe established the Ceramic Repository for the Eastern United States at the Museum of Anthropology at the University of Michigan, and in 1938 the first of a series of conferences on ceramic technology was organized and held at the museum. This was the Conference of Archaeological Technology in Ceramics, sponsored by the US National Research Council and attended by eleven conferees (Shepard and Horton 1939). Subsequent conferences were sponsored by the Wenner-Gren Foundation for Anthropological Research (Viking Fund) and were held in 1961 at Burg Wartenstein, Austria (Matson 1965b), and in 1981 in Lhee, the Netherlands (van der Leeuw and Pritchard 1984).

In the middle of the twentieth century, the first of a regular series of symposia on archaeological chemistry was held at the annual meeting of the American Chemical Society in 1950, with the proceedings published. The late 1950s and early 1960s saw the birth of organized programs of physicochemical analyses of pottery and other artifacts at major research institutions on both sides of the Atlantic. The Oxford Laboratory for Archaeology and the History of Art, for example, focused on optical emission spectroscopy and founded the journal *Archaeometry* in 1958. Brookhaven National Laboratory on Long Island (New York) began applying neutron activation analysis (NAA), a technique with extraordinarily high sensitivity and precision (Bieber et al. 1976: 59; Emeleus 1960; Emeleus and Simpson 1960; Sayre and Dodson 1957; Sayre et al. 1958). Early subjects of concentrated studies included Greek pottery, investigated by both mineralogical (Farnsworth 1964) and spectrochemical (e.g., Catling et al. 1961; Hofmann 1962) techniques, along with Asian (Young and Whitmore 1957) and European (e.g., Musty and Thomas 1962; Richards 1959) wares.

Expanding interest in archaeometric or archaeological science approaches led to the foundation of the *Journal of Archaeological Science* in 1974 and the Society for Archaeological Sciences in 1977; the Materials Research Society, which incorporates study of varied archaeological artifacts, began in 1973. Similar interest in application of research techniques to archaeology developed in the fields of geology (Kempe and Harvey 1983: xiii; Rapp 1977; Rapp and Gifford 1985) with the journal *Geoarchaeology* established in 1986. In the American Ceramic Society one of ten divisions focuses on art and archaeological ceramics, and in 1985 the eminent ceramic engineer W. David Kingery established a publication series entitled Ceramics and Civilization. *Archaeomaterials* was a short-lived journal published between 1986 and 1993.

The late twentieth and early twenty-first centuries saw an explosion of interest in ethnoarchaeological and experimental approaches in pottery studies, initiated by long-

term field and laboratory projects (see sec. 12.1.1). Ethnoarchaeological research strategies focused on potting and non-potting communities and the behaviors relating to pottery manufacture, use, and discard (see, e.g., David and Kramer 2001; Deal 1985, 1988; Gosselain 1994, 2000, 2010; Longacre 1991). The journal *Ethnoarchaeology* began in 2009. Experimental approaches to pottery, often carried out in conjunction with ethnoarchaeological research (see Skibo 2013), reflect increased interest in pottery function: the "pots as tools" view (Braun 1983). These analyses drew on methods and data from ceramic engineering and materials science more generally to assess the physical, mechanical, and thermal properties of a ceramic, whether an ancient fragment, a modern vessel, or test pieces of local clays, formed and fired in a lab.

From these foundations, plus regular meetings sponsored by a range of archaeological societies, a long and distinguished series of articles, international conference proceedings, and other compendia has appeared, treating the complex information that natural science techniques divulge about archaeological pottery (for reviews, see Tite 1999; Vandiver 2001).

14.2 Methods

Numerous attributes of an archaeological ceramic can be the focus of characterization studies, including physical, mechanical, and thermal properties and the mineralogical and chemical composition of both raw materials (clays or clay/temper mixtures) and fired clay objects (table 14.1). Properties of unfired clays or mixtures include color, texture, plasticity, shrinkage, and green strength. In fired ceramic materials, the variables of interest provide evidence of manufacture and characterize the appearance and functional capabilities of the finished piece. New procedures appearing in the recent literature include varied and often automated methods of image analyses, including SEM and three-dimensional surface textural and morphological studies, such as digital and confocal (laser scanning) microscopy (Bevan et al. 2014; Dal Sasso et al. 2014; Kuzminsky and Gardiner 2012)

Table 14.1 Sample Field and Lab Protocol for Ceramic Characterization

	SHERDS	RESOURCES
Field Procedures	Wash, classify, count, catalog, refit, etc. (chap. 13, secs. 14.3, 15.1)	Survey, collect (sec. 14.3.3)
Preliminary Analysis: First Visual Sort	Break corner, sort on attributes of interest: type, form, size, texture, inclusions, hardness, decoration, etc.) (box 4.2, sec. 15.2, box 15.2, chap. 16)	Preliminary testing (plasticity, etc.) (boxes 3.1, 4.1, 4.2; sec. 4.3, chap. 5)
Second Visual Sort: Sample Selection	Select samples for analyses of mineral and physical properties, indications of use, etc. (secs. 15.2.3, 25.3)	Select resources of interest
Mineral Composition and Inclusions	Petrographic thinsections, XRD, SEM, other (sec. 15.2.4, sec. 17.1)	Petrography, XRD, SEM, other (sec. 17.1)
Physical Properties	Measure color, hardness, porosity, etc.; refire; select samples for further analyses based on results (chap. 16, 18, 19) Archaeothermometry (chap. 23)	Form test tiles, measure hardness, color, porosity, etc. (chap. 6, box 16.2)
Chemical Composition	Body: INAA, LA-ICP-MS, PIXE, FTIR Paint, slip, glaze: LA-ICP-MS, XRF (sec. 17.2)	INAA, LA-ICP-MS, PIXE, FTIR (sec. 17.2)

Note: The steps in this suggested protocol are in approximate order and are recursive, as later analyses may prompt re-study or re-measurement of the same or new ceramic materials using earlier procedures. FTIR, Fourier transform infrared spectroscopy; XRF, X-ray fluorescence spectrometry; INAA, instrumental neutron activation analysis; LA-ICP-MS, laser ablation–inductively coupled plasma–mass spectrometry; PIXE, proton [or particle]-induced X-ray emission spectrometry; SEM, scanning electron microscopy; XRD, X-ray diffraction.

The methods selected may be simple or complex, qualitative or quantitative, but they all share the goal of describing the artifact's properties by objective, precise, and replicable standards. The degree of precision and replicability varies by technique, with some retaining elements of subjectivity. Nonetheless, these procedures permit the evaluation of fired pottery and resources in terms relatively free of the aesthetic or qualitative judgments common to art historical appraisals. More important, they yield a database that can be used to relate the properties of the materials—mineral constituents, plasticity, and hardness, for example—to human behavior and decision making in fabrication and consumption.

The precision and replicability of these characterization procedures confer a number of advantages aside from reducing the subjective element. For example, technological data on ceramic properties represent an irreducible minimum of detail on individual objects. They are largely independent of other common categorizations of pottery used

by archaeologists, such as styles, types, and shape categories, yet they can be used for comparing such groupings or creating new ones.

In addition, these methods employ standard units of measurement or comparison that are independent of the context of observation. A pot that would be seen as hard and well fired in one cultural region may be considered relatively poorly fired in another. Describing it as having a Mohs' hardness of 4.0 and being well oxidized at estimated firing temperatures of 800–850°C, however, eliminates the ambiguity of these qualitative terms. Because the results of these analyses are often expressed at the ordinal or interval levels of measurement, varied statistical manipulations can be employed in their interpretation.

With removal of the contextual limitations and use of standard measures, characterization techniques can objectively describe and compare archaeological, ethnographic, and industrial or commercial ceramic materials, whether broken fragments or intact vessels, as well as raw resources. This confers a tremendous potential in geographic areas where known continuities exist between pottery-making communities in the ethnographic present and those of antiquity, because the procedures allow investigation of long-term similarities and changes between manufacturing traditions.

In sum, characterization procedures allow evaluation of hypotheses about similarities, differences, patterns, or changes in large, complex ceramic data sets. They provide a basis for addressing a broad variety of questions about manufacturing procedures, pottery functions, and patterns of local, regional, or extra-regional distributions of pottery. All of these are fundamental research issues in ceramic analysis. To take greatest advantage of these analyses, three closely interrelated issues must be addressed at the start of a characterization project:

- The research question, problem, or objectives must be defined at the outset, and defined in such a way as to be answered, solved, or achieved with highly accurate and precise physicochemical data.
- The samples to be analyzed must be carefully selected so that they (that is, their attributes of interest) will provide the kinds of data that will answer the question via the techniques being considered (chap. 15).
- The method(s) of analysis must be carefully selected to be appropriate for the samples (attributes) to be investigated and to yield the kinds of data needed to answer the question.

14.3 Research Design: Fieldwork and Field Sampling

In ceramic characterization studies, as in any research endeavor, it is important first to define the problem or question, and then to select methods and samples in light of the particular issue(s) to be addressed. As the epigraph of this chapter reminds us, Anna Shepard clearly articulated the reasons for carrying out such analyses in the opening words of her study of Pecos pottery.

Unless an archaeological site (or part of it) was excavated precisely because it was a known location of pottery manufacture, the recovered pottery is usually obtained through pursuit of some other research goal. Thus it is useful to consider the relations between a collection of excavated pottery and the source site itself: What does that pottery actually represent in terms of past people and their activities? More specific concerns relate to the subsampling of excavated pottery collections for varied purposes, such as reconstructing pottery assemblages and site activities, and for certain technical analyses.

The innumerable methodological issues of archaeological site sampling lie well outside the scope of the present work and in American anthropological archaeology these were extensively debated in conjunction with the paradigm shifts of the 1960s and early 1970s (see, e.g., Benfer 1975; Cowgill 1964; Mueller 1975b; Redman 1974; Vescelius 1960; more recently Drennan 2010: 79–132; Orton 2000). Given that it is rare for an entire site to be excavated—and sometimes a large site's precise boundaries are not even known—an archaeological pottery collection almost never constitutes all the pottery from an entire site. Instead, the collection is usually a sample of that total population of an unknown number of whole and broken vessels, types, forms, figurines, and other ceramic artifacts (beads, weights, toys, etc.).

Two fieldwork issues are of particular concern at the start of a ceramic analysis: one is the basis for selecting areas to be excavated and the techniques by which they were dug and artifacts recovered; the second is how the pottery was recovered and processed in the field. The analyst may or may not have a say in these matters.

14.3.1 Excavation Loci

Areas selected for excavation may have been chosen in any number of ways: purposively or judgmentally to explore some specific aspect of the site, such as a particular structure or zone; by haphazard or grab sampling for logistic convenience or to satisfy some nonscientific criterion; or by a probabilistic sampling strategy. In this last procedure the total area of the site is typically divided into equal units, and then individual units are selected for excavation by a method in which each has a known probability of being chosen (the sampling frame). Examples of such probability sampling strategies are simple random, stratified, and systematic sampling.

Each excavation strategy has practical merits, depending on the overall project goals, but they also have ramifications for pottery analysis and its objectives. If all that is desired is a description of the pottery found in the excavations, sample selection is not highly significant. But if the aim is to draw some conclusions about the pottery at the site as a whole from the smaller amount of excavated material—that is, to generalize from the excavated sample to the total population of pottery (the target population, or universe), and its makers and users—this is a different matter entirely, particularly at a large site. Generalizing the characteristics of a larger population from a small sample is a matter of inferential statistics, and statistical models require that the sample fairly represents the range of variability within the relevant characteristics of the population. Such generalizations can be made only if excavation units are selected by a probabilistic sampling procedure, because other sample selection methods have a greater risk of imposing known or unknown biases on the data recovered.

A related, if somewhat abstractly technical, point is that excavated artifact samples from archaeological sites are cluster samples (Cowgill 1964; Mueller 1975a; Orton 2000; Vescelius 1960). That is, the probabilistic excavation sampling strategy by which the artifacts, in this case pottery sherds, are recovered does not yield a sample from an identified population of itemized sherds, because the artifactual population of a site (the target population) cannot be known in advance of excavation (the sampling paradox). Instead, the sample of pottery is recovered from a population of horizontal and vertical spatial units of the site, and these excavated units contain groups (or clusters) of many items such as sherds. In other words, the artifacts themselves are not sampled independently and directly by excavation. Rather, they constitute clusters of items that proceed fortuitously from the actual sampled units. This distinction has further implications for calculating the characteristics of the population of artifacts at the site from the excavated sample, should that be the object of the analysis.

14.3.2 Recovery and Processing

It is important to understand a site's excavation procedures to determine whether comparable conditions of recovery were maintained among excavation units. These concerns include the size of excavation units, definition of levels, and use of screening and flotation: variability in these procedures can result in differential recovery and skewed quantitative comparisons. Similarly, piece-plotting of pottery fragments can aid in estimating numbers of whole vessels and comparing relative quantities. Processing of excavated pottery, such as washing it, demands careful attention to avoid removing delicate post-firing substances such as painted stucco, or residues from cooking, burning incense, or other activities, and to avoid creating pseudo-attritional marks resembling usewear. If whole vessels are encountered, their contents—even if it appears to be merely dirt from the soil matrix—should be carefully preserved for future

analysis (e.g., identification of microbotanicals). Data recording procedures are generally specific to individual projects and traditional practices in a region.

If physicochemical investigations of the pottery are anticipated, a ceramic technologist, archaeometrist, or someone skilled in such analysis should be consulted before fieldwork begins to discuss objectives, methods, and limitations, with particular attention to contamination that can occur by standard procedures of washing, drying, cataloging, and conserving artifacts. Ideally, the consultant should be in the field for a significant portion of the fieldwork so as to be familiar with the excavation contexts and geological situation. It is particularly desirable to have such a consultant, or an anthropologist studying contemporary pottery manufacturing, present in the field to sample resources.

14.3.3 Collecting Resources

Ceramic technological investigations, whether of archaeological or ethnographic materials and whether or not conducted through the perspectives of ceramic ecology, are enhanced by a resource survey to identify deposits of local clays to compare with the pottery of interest (see Hegmon and Neff 1993; Talbott 1984). Possible sources of tempering agents, pigments, and other important pottery constituents (glazes, mineral coatings) also should be identified. A massive raw materials survey undertaken by Hector Neff and his colleagues (1992) in Pacific coastal Guatemala covered 4000 sq km and sampled 150 clays and 26 tempers, serving as a model for such projects (see also Falabella et al. 2013).

At the archaeological site itself, excavators should take special care with unusual earthy deposits in the debris of rooms or compounds (Jeancon 1923: 36–37; Southward and Kamilli 1983), because these could be potter's clays. In addition, clays or clayey soils within or underlying cultural deposits also should be noted.

The easiest way to locate suitable clays and other resources near an archaeological site is to ask local informants. If contemporary communities of traditional potters are in the area, or studio potters who work with natural clays, they may be willing to divulge where they obtain their materials. Sometimes street or neighborhood names reflect the earlier existence of clay mines or potting industries. Elderly residents in rural areas may remember former potters and know where they obtained their clays; workers in modern farming or construction activity—excavating house foundations, laying sewer pipe, and so forth—also may have encountered clays or clayey soils.

Local soil and geological maps should be consulted for information about hydrological patterns, soils and subsoils, and variations in geological deposits. These maps, however, are rarely at a fine enough scale to be satisfactory for clay location purposes, they may record only commercially valuable clay deposits, and soil charts may have been created by recording differences in standing vegetation as proxies. Nonetheless, it can be useful to travel along river or stream courses, lakeshores, or

estuaries looking for clays, or outcrops or bluffs with clayey deposits exposed or weathered out. An area within a radius of about 7 km from the site of interest should be given greatest attention, because this appears to be a primary catchment for potters to procure resources (see sec. 8.1.1).

A soil auger may help determine the location or extent of buried clay deposits (see Shackley 1975: 24–29). However, the full extent of clay beds and their variability can rarely be comprehended, because they extend for unknown horizontal and vertical distances beneath the surface of the earth. In all situations, it is advisable to remove multiple samples of the material both vertically and horizontally (Talbott 1984: 1048–49), to investigate natural compositional variations resulting from the original conditions of deposition.

Considerations of space, cost, and distance make it useful to carry out preliminary tests of the workability of a clay before transporting it to the laboratory. A small pinch of wet clay (or dry clay with water added) can be squeezed, rolled into a rope, and twisted to get some idea of workability. A deposit that is extremely coarse and sandy or mealy and cracks under slight pressure is not likely to have been suitable for potting and may not warrant collecting a large sample.

For all clay deposits and other resources identified, a standardized reporting form should be used to record essential information (table 14.2). This form should include data on the deposits underlying and overlying the clay, the color and texture of the material, how the deposit was exposed, the thickness of the deposit, kind and degree of known or probable contamination (such as rootlets), and so forth.

In extracting a sample of a clay, it is most important to avoid contaminating it with soil or other materials, a serious problem in sensitive chemical analyses. If the deposit is an outcrop, stream bank, or some other more or less vertical exposure, its face should be carefully scraped with a clean trowel back to a depth of at least 10 cm. This will reduce surface contamination and expose a fresh area for sampling. Where there is a horizontal exposure, the same guideline applies. In auger testing, the danger of contamination from the coring procedure is a serious disadvantage.

The amount of material sampled often depends on conditions of exposure and the logistics of transportation. Although the actual sample necessary for mineral or chemical analysis is tiny—only a few grams at most—it is useful to have much greater quantities for tests of workability, plasticity, firing experiments, and so forth as described in Part 2. In addition, to achieve some degree of representativeness for chemical characterization, a larger amount of the material is usually prepared and repeatedly subdivided for sampling. Finally, given the volatile political situation in many areas of the world, it may be impossible (or prohibitively expensive) to return later to collect more of the material. Importing soils from another country may be prohibited or restricted; in the United States, it is necessary to have an import permit from the US Department of Agriculture.

Table 14.2 A Clay Sample Recording Form

Sample #: _____

Date: _____

Collector: _____

Collection location:

Thickness of deposit:

Form and extent of deposit:

How exposed:

Characteristics in situ:

Material overlying:

Material underlying:

Surrounding natural features:

Cultural features:

Amount sampled:

Other remarks:

For maximum experimental usefulness, a sample of approximately 5 kg, approximately a bucketful, is usually satisfactory. The clay should be removed with a clean shovel, trowel, or auger, with special care to avoid contamination with surface soil or other foreign matter, placed in a clean plastic bag, and immediately sealed and labeled with an identification name or number, or both, keyed to the recording form. Double bagging is advisable, with the label placed between the two bags rather than inside with the clay.

14.4 Interpretation

Interpreting the behavioral significance of quantitative and qualitative physicochemical characterization of ceramic materials and variations between classes of pottery is an independent procedure that is not strictly contingent upon the technique itself. Several cautions are in order.

One caution is that highly technical studies can bestow a false sense of precision. The selection and testing of materials in ceramic engineering research are considerably more standardized than they are in non-industrialized pottery manufacture (e.g., Rye 1981: 27–28), thus the "purity" (in the sense of composition, particle size, etc.) of the ceramic materials being tested and the experimental conditions are far more controlled. Many of these tests confer the additional advantage of precise measurement of variables in units such as micrometers or milligrams. In anthropology and archaeology, however, the socioeconomic concepts investigated through pottery are rarely if ever formulated with comparable precision, nor can they be experimentally controlled with similar exactitude. Thus, although certain tests and measurements may be significant statistically or with respect to engineering standards, they may not be behaviorally significant in, or to, the cultural context investigated.

Another caution is that although technical tests allow objective description of pottery, subjectivity still enters the interpretation of the results. Thus judgments of vessels as "poorly" made, for example, are best avoided. At the very least, interpretations should be phrased within a comparative framework relative to the specific context under investigation. Vessels that to twenty-first-century eyes may seem coarse, porous, and underfired may represent a set of carefully developed accommodations to the peculiar properties of the resources locally available as well as to certain use requirements (e.g., Frink and Harry 2008).

Also, there may be some internal variability in the properties of the vessels of a single firing load. Given the highly variable conditions of open firings (and often updraft kilns), vessels and their properties may vary as a consequence of fluctuating temperature and atmosphere, even comparing one side of the pot with the other.

In addition, the measurements and other findings with respect to the analyzed properties and performance of a sherd are not necessarily or precisely those of the original ceramic. They may be reasonably close, depending on the age and context of recovery of the material. But they are better considered as approximations—remnant properties—that may register aspects of the original characteristics along with alterations brought about by postdepositional circumstances.

Significant differences in properties between two or more vessel categories (forms, decorative classes, etc.) may represent conscious choices made by the potter and may corroborate structural or physical principles of engineering, mineralogy, or chemistry. They cannot necessarily be assumed to represent such decisions, however, unless

alternative possibilities (including postdepositional alteration and chance alone) can be eliminated. Association between variables, in ceramics as in general, is simply a statement of relation between those variables and does not automatically reflect human intent: correlation does not prove causation.

Finally, it is important to recall, yet again, that the resources used by a potter in making the vessel in question are but samples of a larger entity or population. Similarly, because archaeological sites are almost never excavated in their entirety, the true population of ceramic vessels at a site is never known. An excavated sherd and vessel collection is itself a sample of the site; the collection may or may not be a fair representation of the complete ancient assemblage, and it is better considered as the available population rather than the true population. Consequently it is impossible to know if the sample selected from the collection is proportional to any existing reality in ancient times. The ramifications of these uncertainties for interpretation of ceramic data have been virtually ignored, although similar problems for archaeological data in general are of long-standing concern.

The more complex and sophisticated the method of analysis of pottery, the more difficult it is to interpret the results behaviorally because of the more general problems of translating mineral and chemical data into human decision-making in antiquity. This interpretational leap is made easier when one begins with simple but large-scale field observations on the physical properties of a ceramic collection, plus the properties of available raw resources. These characteristics relate most directly to the relations between human behavior and the environment: the properties of the resources, the potter's choices and decisions about selecting and preparing them and about forming and firing a vessel, and the object's final appearance and use. Whether resource selection was or is a matter of tradition and custom or of unfettered choice, the process rarely involves the potter consciously discriminating one mineral (or chemical) species from another in Western scientific terms. Rather, it involves the potter understanding that a particular resource confers some desirable *property* or set of properties to the finished product.

Characterization analyses must be interpreted within some sort of broader framework in which technological properties are framed as manifestations of nonrandom occurrence or human action, and that action in turn must be conceptualized within a cultural or historical context involving the production, distribution, use, or discard of ceramic materials. This interpretive transition or translation is not easy. Although the technical instrumentation of materials analysis has advanced to extreme sophistication, there has not been a corresponding development of middle-range theory or formation theory (see Shott 1998)—a body of relational statements—to bridge the gap between technological data and sociocultural theories, and allow archaeologists to take advantage of the technological precision. Nonetheless, translating the technological to the cultural is a basic and unavoidable research responsibility in the analysis of ceramic materials.

There are, of course, varied ways to make this transition, and many are interrelated. Ceramic ecology is a restatement of earlier ideas on the relation of cultural interpretations of technical data—for example, the concept of "techniculture" (Osgood 1951). Raymond H. Thompson (1958: 6) borrowed this concept in his study of continuities between ancient and modern Maya pottery in Yucatán, noting that the "technical and ecological factors which condition the properties, source, and availability of raw materials define a specific range of possibilities for the manufacture of any class of artifacts." Many of the criteria for defining this range of possibilities come from the various natural and physical sciences; these provide the basis for investigating such properties as plasticity, strength, shrinkage, and vitrification point. The technical observations and measurements from any artifact must be linked to inferences about human behavior involved in its production and use, however, and this is the "technicultural" objective of analyses of material culture. Thompson uses pottery as an example:

> Basic to the interpretation of ceramic evidence is the generalization that clay becomes plastic when mixed with water. But the significance of this generalization to a specific type of archaeological ceramics is obscured unless the technological data are rephrased to emphasize some use which man makes of this plastic property. This shift in emphasis from the purely technical property to the use to which man puts it introduces cultural factor. The generalization then becomes a technicultural combination, technical data in a cultural frame of reference.
>
> *(Thompson 1958: 7)*

A similar point of view exists in the ceramic engineering literature: "Data taking alone is not valid characterization regardless of how sophisticated the technique may be —correlation of the data with properties and behavior is essential for characterization to be meaningful" (Hench 1971: 4). And a complementary interpretation is offered by Heather Lechtman (1977). Arguing that technologies represent activities or "performances" carried out in culturally prescribed ways, she feels that anthropologists and archaeologists should exploit this information to study technological styles:

> The culturally accepted rules of the performance are embodied in the events that led to the production of the artifact. We should be able to "read" those events, if not all of them at least those of a technical nature, through laboratory study of the materials that make up the artifacts in question. The history of the manipulation of those materials is locked into their physical and chemical structure: the methods of material science can interpret that technological history.
>
> *(Lechtman 1977: 14)*

15 Quantification and Sampling Collections

> The rules of statistics were not on the tablets Moses brought down from the mountain.
>
> Drennan 2010: vi

Classifying and cataloging the pottery recovered at an archaeological site are basic first steps of proper methodology, but these are only first steps. Most field projects incorporate further analyses into their research designs, which typically necessitate assessments of "how much" pottery is in the collection. A goal might be to determine how many vessels existed in one or more subunits or proveniences of a site (structures, burials, features, etc.) or at the site as a whole. This latter emphasizes the importance of knowing what proportion of the site was excavated to yield the pottery being studied.

Because excavation programs may yield thousands or tens of thousands of fragments, additional decisions must be made about what should be given further study to provide insights about the locale's original inhabitants' pottery manufacture and use. Thus a key step for many kinds of pottery analysis—indeed, in any scientific approach to large bodies of data—is collections sampling: deciding which and how many objects to study, and which to ignore. This chapter covers many aspects of selecting samples of pottery for study, including selecting sherds for physicochemical analyses.

15.1 Quantification

Quantification or the "quantitative idiom" refers to "recognition that measurement and the manipulation of numbers are . . . a useful way to obtain insight into some phenomenon or process" (Aldenderfer 1998: 93). Pottery and other categories of artifacts are typically subject to three kinds of quantification:

- Simple frequency counts of sherds or vessels;
- Measurement of some attribute(s) of interest; and
- Descriptive and inferential statistical analysis.

In the case of pottery, a fourth and more complex concern arises: the relation between the broken fragments recovered at a site (in archaeological context) and the number of whole vessels in actual use by the occupants (systemic context). This is the "unit of observation" problem: the site's residents primarily occupied themselves with functional assemblages of whole pots, rather than with broken fragments. To reconstruct behavior of manufacture and use, these fragments must be translated into numbers of whole vessels originally present.

15.1.1 Counts and Measurements

Quantitative studies generally begin with simple tabulations of amounts of material in different categories of interest (such as types or shapes) from various sites or parts of sites. These raw frequency counts of individual sherds, however, tell little more than how many fragments were excavated and processed in the field lab during a season or project—that is, a crude index of project labor. They say little relevant to the actual amounts of pottery in systemic context at the site because the former inhabitants possessed whole pots, not fragments of them, in their domestic activities and rituals.

Measurement refers to "the assignment of numbers to objects . . . in accord with some rule" (Kaplan 1964: 177). As with data, measurement "is not a useful exercise in and of itself: its meaning derives from the context of the theory within which we gather our data" (Aldenderfer 1998: 93). Useful measurements or quantitative analyses of pottery may be dimensional or compositional, and the theory within which these numbers are assigned typically (but not exclusively) relates to socioeconomic questions about production, consumption, and exchange.

15.1.2 Statistical Analysis

Statistics is a third aspect of pottery quantification that is of interest to archaeologists (e.g., Baxter 2010; Drennan 2010; Orton 2000; Shennan 1997; VanPool and Leonard 2010). Statistics refers to a set of tools for thinking about data and measurements, and can be categorized as descriptive and inferential. Both allow identification of patterns or structure in a dataset.

Descriptive statistics summarize and characterize the observations on a collection of pottery in ways that allow the researcher to see what is "average" or typical and what is extreme for a limited number of variables. Descriptive statistics include simple indices such as the mean, median, mode, standard deviation, variance, and range. These can be displayed graphically in numerous ways, including histograms and various kinds of box plots or scatterplots.

The methods of inferential statistics range from relatively simple operations, such as tests of significance (see, e.g., Sinopoli 1991: 171–210), to sophisticated multivariate techniques. Inferential statistical methods are modeled on sampling theory and probability theory, and they permit, with varying degrees of confidence, inferences or generalizations from a sample, such as the pottery excavated from parts of a site, to the entire site or target population. Many assumptions are involved in these models of relations between a sample and a population, and the specific parameters of the relations are the basis for distinguishing parametric and nonparametric (fewer assumptions) statistics. Serious problems in analyses of archaeological data may arise because of uncertainties about these relations and consultation with a trained statistician is usually advised.

Multivariate statistics or analyses (for an introduction to a large literature, see Baxter 1994; Romesburg 2004; VanPool and Leonard 2010) are still more complex models for discovering underlying patterns and structure in a body of (usually) quantitative data. These types of calculations, such as principal components and cluster analyses, are typically carried out in conjunction with compositional analyses of pottery (chap. 17), in which ten to thirty or more variables might be considered simultaneously. Above all, "preliminary data inspection is essential before undertaking any form of multivariate data analysis. . . . and a willingness to let commonsense override any itch to use multivariate methods because they are there, cannot be overemphasised" (Baxter 1994: 27). Cluster analysis (see Baxter 2009), because it is closely comparable with archaeological classification (grouping), is an intuitively grasped procedure. Some programs such as CLUSTAN (http://www.clustan.com/) allow analysis of the combined qualitative and quantitative ("mixed level") data that are so common to pottery analyses (Rice and Saffer 1982).

15.1.3 Sherds to Pots

As noted, an important concern in quantifying pottery is the unit of analysis: the broken pottery fragments recovered in excavations represent what were originally intact vessels used by the occupants of the site. The translation of raw sherd counts into whole pots underlies transitions from the archaeological context of sherd assemblages to the systemic context of functional containers and interpretations of pottery use and assemblage composition.

Raw sherd counts in effect consider each fragment to represent a vessel. They nearly always provide misleading or biased estimates of numbers of whole vessels because there is no simple relation between a vessel's size or shape and the number of sherds it breaks into (see, e.g., Deal 1983: 201–2; Kirkby and Kirkby 1976: 237; Orton et al. 1993: 169; Reid 1984; Solheim 1984: 101). Large vessels typically break into more pieces than small vessels; thin-walled pots may break into more sherds than thick-walled pots; low-fired pieces may break into more fragments than high-fired objects; different parts of a site may have experienced different taphonomic processes: patterns of activity that caused more or less primary or secondary breakage. The result is that vessels that break into more sherds (or are subject to more disturbance or weathering in middens after discard) will be overrepresented in a given excavation unit.

Tallying vessels rather than sherds is important because research goals may involve comparisons of pottery from different proveniences, such as sites, levels, structures, graves, features, and so on. It might be of interest to know, for example, if one domestic structure (or residential area or site, etc.) had greater access to a nonlocal pottery type than did another. Imagine two neighboring residential compounds, A and B, at a site 300 km from a village that produced a beautiful and widely traded ware known as Type Q. If complete excavation of House A yielded 232 sherds of Q and complete excavation of House B yielded 147 sherds of Q, the archaeologist's simplest inference would be that A had greater access to and possessed "more" of the nonlocal Type Q pottery. These figures might lead to interpretations of status differences between A and B, or of biological, marital, political, or religious affiliations with the producing site, and so on.

But suppose written records (or a time machine) revealed that the occupants of A and B each had 5 bowls of Type Q. Why are the sherd counts misleading? They are misleading because, as ethnoarchaeological research has shown, a host of behaviors and processes affect breakage and movement from systemic to archaeological context. House A might have had more children and dogs responsible for greater breakage and trampling. The residents of B might have swept up some of their kitchen debris with Q sherds and taken it to a dump outside the compound. House A might have used its Type Q bowls more frequently than did B. House B's bowls might have been of different sizes, thicknesses, and uses than A.

This example illustrates that quantification may be simple but it is not always straightforward. Because so many variables can confound the relationship between sherds and whole vessels, even within a single type or form, and because whole vessels are more culturally relevant units of analysis and interpretation than fragments, comparisons between recovery locations require that some adjustments be made.

Box 15.1 Translating Sherds into Pots

Numerous procedures, of variable degrees of complexity and accuracy, can be implemented to begin to transform pottery fragments into tallies of whole vessels (see Orton 1993; Orton et al. 1993: 166–81). The simplest is cross-mending or re-fitting: if two or more fragments can be joined together, counting the joined pieces as single sherds is a closer approximation of the actual number of individual vessels than is a simple count of all sherds. Absent conjoinable sherds, matches can be identified through digital imagery from thin sections (Blanco-González et al. 2014; also Blanco-González and Chapman 2014). Counts can be reported as before- or after-mending totals, but both measures generally overestimate the number of vessels at a site.

Another simple procedure is to sort a collection into meaningful categories, such as wares, types, forms, etc. Within these categories, individual vessels can be estimated by counting the numbers of rims, bases, handles, or other distinctive parts that occur in known frequencies on pots (for example, two-handled ollas, or single-spouted jars, or tripod plates). Base sherds may be more accurate than rims in predicting the total number of vessels in an assemblage (Frankin 1971: 250). Proveniences of interest then can be compared.

A slightly more complex procedure for comparative purposes is to standardize raw counts against some other unit to create ratios. This ratio can be calculated as number of sherds per unit of excavated volume (e.g., cubic meters) of the provenience(s), but if the size of the excavation unit is small (e.g., 1 x 1 m) and/or if discrete levels are thin (e.g., 10 cm) these calculations can be cumbersome. Sherd ratios also can be calculated in terms of frequencies of other artifacts, such as numbers of sherds per counts of lithics.

An index of ubiquity may be calculated for pottery, as it is for taxa in environmental studies. The ubiquity index measures the proportional or relative presence (presence-absence) of an item of interest (e.g., a type or form) in the available samples, such as proveniences. Ranging in value from 1.0 (present in all samples) to zero (absent in all samples), the index is calculated as the number of samples/proveniences containing the item divided by the total number of proveniences (see Popper 1988: 60–64).

Sherd weight has sometimes been touted as a more accurate quantitative indicator of numbers of pots than are sherd counts (Baumhoff and Heizer 1959; Chase 1985; Solheim 1960). Sherd weight effectively standardizes the data for differences caused by large versus small sherd sizes or thicknesses, which also may result from differences in disturbance and comminution in certain areas of a site. It is frequently recommended that both sherd counts (after mending) and weights be recorded to compensate for the inadequacies of each measure (table 15.1).

Table 15.1 Percentages of Sherds by Weight and Count from a Test Pit at Site 17, Fiji

	Depth in Inches								
Classes of Sherds	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**48**	**74**
Plain									
Percentage weight	79.0	80.0	81.0	82.5	76.5	74.5	47.5	49.5	45.0
Percentage by count	89.0	90.0	91.0	90.0	89.0	82.0	60.0	60.0	60.0
Number of sherds/oz.	7.5	8.0	7.0	8.0	8.0	9.0	8.0	7.0	6.0
Incised									
Percentage weight	17.0	16.0	14.0	10.5	10.0	3.5	0.5	. . .	. . .
Percentage by count	9.0	7.5	4.5	5.0	4.0	1.0	0.3	. . .	. . .
Number of sherds/oz.	4.0	3.0	2.0	3.0	3.0	4.0	4.0	. . .	. . .
Relief									
Percentage weight	4.0	4.0	5.0	7.0	13.5	22.0	52.0	50.5	55.5
Percentage by count	2.0	2.5	5.0	5.0	7.0	16.0	39.5	40.0	34.0
Number of sherds/oz.	5.0	4.0	6.5	5.0	4.0	7.0	4.0	4.0	3.0

Source: After Deal 1983: table 33. The data in Deal's table were taken from Gifford 1976: tables 17 and 18.

Sherd weight totals may be converted to numbers of vessels by several procedures. One requires that the sherd collection be separated into form or type categories, with a whole or reconstructible vessel present for each category. The complete vessel is weighed and the sherd categories are weighed; then the weight totals are divided by the weight of the individual vessel. This gives some idea of the numbers of pots for each category and for the collection as a whole (see, e.g., Vitelli 1989: 21–22). Closer estimates are possible if this procedure is combined with estimates of the numbers of individual vessels based on rims, bases, handles, spouts, and so on.

A second weight-based procedure estimates proportions of vessel categories by comparing size classes, using the assumption that the weight of a vessel is proportional to its surface (times thickness). Vessels are sorted into size categories, total category weights are determined, and the average body diameter (radius) is estimated for each category. For example, if large pots have an average radius of nine inches and small ones have an average radius of two inches, then the ratio of the weights can be given by comparing the ratios of their surface areas: $4\pi(r)^2$. The larger vessels are 20 times as heavy as smaller ones, and the weight totals for vessels in the large class should be divided by 20 to estimate the proportion of large and small pots in the whole collection (Baumhoff and Heizer 1959: 312). Application of this procedure is limited by the assumption of spherical shape.

More precise approaches to pottery quantification involve complex data transformations (see Deal 1983: 251–67; Orton 1982; Orton et al. 1993: 21, 171–73). One such approach is to calculate vessel

equivalents or estimated vessel equivalents (EVEs), which may be accomplished in several ways. Calculating minimum number of vessels (MNV) or number of inferred vessels (NIV) is analogous to the zooarchaeological procedure of determining minimum numbers of individuals (MNI) of faunal species, and for pottery two methods have been proposed (Millett 1979b: 77–78).

One is the subjective assessment and grouping of all sherds that definitely do, or at least might, represent a single ceramic object. This procedure may be fairly useful, but it lacks replicability and tends to underestimate the number of vessels actually present. Several related procedures build on counts and measurement of rim sherds, bases, or handles sorted by ware or type. Rim equivalents, for example, may be calculated from the lengths (or percentages) of rims of a particular type of pot, which then may be divided by the mean rim diameter (Egloff 1973); similarly, the length of the arc of the rim sherd can be divided by the total rim circumference (DeBoer 1974: 340; Plog 1985). The easiest way to carry out these measurements is with a diameter template that shows both radius in centimeters and percentage of the total orifice circumference (fig. 13.7). A combination of these procedures may be used to calculate estimated vessel equivalents: the total rim equivalents and base equivalents are added together, and the total is divided by two (Orton 1980: 166).

The disadvantage of rim- and base-focused techniques is that they ignore body sherds and are difficult to use with extremely small rim fragments for which diameter measurements are unobtainable. It is also important to consider the possibility of differential preservation of rim sherds, which in some cases are curved and may be thinned and relatively more fragile, and in other cases may be thicker, with entire jar necks and rims preserved. Similarly, bases are often thickened and therefore stronger and less likely to break.

Additional problems are posed by previously discussed issues of sampling areas of a site and the relation of those areas to patterns of use, discard, and postdepositional fragmentation of pottery.

15.2 Sampling

Most excavations of archaeological sites dating within the last five thousand to ten thousand years or so yield enormous collections of fired clay artifacts, the most abundant being fragments of pottery containers. Because of cost and time, however, not all can be given complete individual characterization. Thus it falls to the analyst to select a sample of sherds (or pots) for analysis. It is impossible to know beforehand what materials can be safely ignored or discarded in sampling a collection—this is known as the "sampling paradox"—yet such seemingly arbitrary decisions must be made for pragmatic reasons. Quantitative studies of large sherd collections have been discussed at length (Cowgill 1964; Keighley 1973; Solheim 1960), sometimes in conjunction with mineralogical or chemical characterization projects.

Sampling considerations relating to pottery are discussed here in terms of selecting items from large collections and for various kinds of characterization studies. They are relevant to pottery fresh from the field as well as the enormous stored collections of artifacts in the world's museums (see, e.g., Washburn et al. 2014). These latter are frequently shunned because they were excavated decades ago, before today's more rigorous standards of scientific procedure. Although the exact date and provenience information of these sherds may be lost, they often are from easily identifiable types, forms, or wares and curators may even consider them relatively expendable for examination by destructive methods.

15.2.1 Sampling Pottery Collections

Ideally, sherds selected for analysis from a larger collection should represent well-documented archaeological contexts—that is, carefully excavated locations with unambiguous cultural significance. If possible, vessels or fragments should be from sealed stratigraphic contexts (pits, burials, storage areas, etc.), from deposits of known date, and/or from units that can be clearly identified or differentiated as to status and residential, ethnic, or functional associations (or other matters of interest). These are ideal conditions, and frequently the pragmatics of archaeological excavations do not permit all to be satisfied.

The appropriate sampling criteria for a pottery collection derive from the research question or problem being addressed. This question may be closely aligned with that guiding the excavation project that led to the pottery's recovery or independent of it. Thus the first issue is to define the research question or problem to be addressed through pottery characterization. Subsequent decisions and procedures derive from that problem statement.

The next set of decisions involves determining what kind(s) of pottery and what aspect(s) of the pottery—that is, which attribute or set of attributes—is most likely to contribute answers to that question or problem. The attribute(s) might be typological,

technological, decorative, formal, functional, contextual, or any combination of these or others.

Another set of decisions concerns whether the focus is to be on the material considered more common or typical in the collection, or on the unusual, or on identifying the range of variation on the attribute(s) of interest. The range of variation in human behavior and artifacts has a special significance in ceramic characterization studies:

> The classificatory and control devices used by potters in the past have usually been far less precise than our facilities for analyzing their results. Materials that vary widely according to our physical and chemical measurements may have been considered identical or interchangeable. Methods of measurement were also less sensitive. Materials for blending, for example, were often calculated by volume rather than weight. Potters using clay and sand mixes might judge that "two handfuls of sand is enough for this much clay." Although our measurements might determine that the proportion of sand varies between 20 and 45 percent, this variability might be viewed by the potter as within the normal range. . . . Similarly, firing temperatures, whether in open firings or kilns, can vary not only between firings and within settings, but over parts of a single vessel by as much as 400°C. The same latitude applies to the shapes of vessels; the criteria used by a potter to judge that two vessels are the "same" may be difficult or impossible to reconstruct. Thus, the parameters for defining a technological tradition cannot be specified until the range of variations encompassed within the tradition can be differentiated from characteristics that are outside the "normal" range.
>
> *(Rye 1981: 27–28)*

Regardless of the attributes selected, then, it is valuable to work within a frame of reference that incorporates the variability of the entire collection. The prevailing direction of the variations from the norm (toward darker rather than lighter colors, or coarser rather than finer texture, for example) will be informative. Or, variants may represent rarities or presumed nonlocal items, or extremely early or late examples, or unusual contexts. The range serves as a basis for selecting smaller subsamples for more specialized analyses as the analysis proceeds, and establishes the context for interpreting further findings.

In addition, understanding the range of variation will help answer the always-difficult question of sample size: How many sherds (or pots) do I need to analyze to be confident in generalizing my findings? A general sampling rule of thumb is that the more heterogeneous the population, the larger the sample required for representativeness. Another way of saying this is that the larger the sample, the greater the likelihood that it represents the total range of variability in the collection.

Large collections usually require "stratified sampling." That is, the collection should be divided into strata or subgroups on the basis of some single criterion that is deemed key to the goal of the research. If the goal is to characterize or understand similarities and differences in pottery among contexts, the collection might be stratified into material from burials, domestic, ceremonial, and defensive structures. Similarly, if the research goal relates to technology, a collection might be stratified by temper, as ash, limestone, and grog; or by red, black, and cream slip colors. Individual sherds are then

selected separately from each stratum (by simple random or systematic sampling). Strata may be substratified, for a nested approach to sampling. Stratification ensures that the major variations (attribute states) in the criterion (attribute or variable) relevant to the research question are included, thus improving the representativeness of the sample.

Several further considerations merit mention:

- The sampled sherds should represent different vessels (unless intra-vessel variability is the research goal).
- Sherds should have well-preserved surfaces, with little or no evidence of postdepositional erosion, encrustation, discoloration, or mineralization (unless that is the subject of the study; e.g., Beck et al. 2002; Secco et al. 2011).
- As many sherds as possible should be selected, within existing financial, temporal, and permitting constraints.
- Were the materials glued or painted in reconstruction of vessels or exposed to chemicals for cleaning, preservation, or fumigation? If so, chemical analysis may be ill-advised.
- The sherds chosen should be as large as possible to allow removal of fragments for further testing (e.g., chapters 17–19), but . . .
- . . . it must first be ascertained if such damage is permitted by the materials' custodians (a museum; another country).
- Must any special precautions be taken in excavating, handling, or transporting the artifact?

15.2.2 Selecting Individual Sherds

A guiding principle in selecting pottery fragments for analysis is to maximize the amount of information inherent in each sampled sherd, so that not only is the variable(s) of stratification represented, but also other attributes are present. For example, it is useful to select sherds representing a range of areas on the vessel, including the rim, body, and appendages (supports, handles, spouts, etc.) if form was not the basis of sample selection. Similarly, it is useful to have stylistic information (slips, paint, motifs) preserved on the sherd surfaces if decoration was not the primary variable. These considerations provide additional information on the fragments that may prove useful in interpreting differences in analytical findings.

Regardless of the basis of the stratification, several points underlie the selection of individual sherds for further study:

- First, Break a Corner.

  As a preliminary to any understanding of the technology of archaeological pottery, a tiny corner of each sherd should be broken off with snub-nosed pliers. Breaking a corner permits examination of the paste in a fresh cross-section, free of surface contamination. This, in turn, allows the sherds to be sorted on the basis of variables that are important in characterization studies if these were not part of stratification. Such variables include color (including dark coring and preliminary inferences about firing), fracture characteristics, and texture (inclusions, porosity). Creating and examining a fresh break permits a quick assessment of the technological and compositional heterogeneity of a collection without significant investment of time or equipment.
- Start Simple.

  Any program of technological or compositional analysis of a pottery collection should begin with the simplest "low-tech" (or "no-tech") observations and techniques, and work up to more complex and "high-

tech" procedures (table 14.1). Simple techniques and tools—a 10x hand lens and pliers—can be rapidly and easily applied to large collections of ceramic materials in the field (or in a museum). Hardness can be rough-sorted by scratching the surface with a fingernail or a penknife, or by the sound when a sherd is tapped against a hard surface, or by the way a sherd fractures when broken. A hard sherd may be difficult to break and fracture with a snap, leaving clean edges, while a "softer" sherd may break more easily with a crumbly or friable fracture edge. General estimates of quantities of inclusions may be obtained by comparison with prepared standards, either diagrams (fig. 15.1) or prepared mixtures of local clays and different amounts of sizes of inclusions. These simple procedures provide an additional quick scan for determining the range of variability of the collection on several significant physical properties.

· Put Mineral before Chemical.

As part of the "start simple" approach, it is generally advisable to undertake a mineral analysis before a chemical study, especially with low-fired earthenwares, unless specific questions have been previously formulated about chemical composition with comparative data. Characterization studies of the composition of archaeological pottery are frequently undertaken to determine its provenience, now often called provenance: where the item was made. This goal warrants selection from the full array of advanced methods for mineralogical and chemical analysis. Each suite of techniques tells very different things about the ceramic, which has important ramifications for structuring research.

Mineralogical composition is basic. It is related to virtually all the physical properties, not just to texture and porosity but also to hardness, color, and strength, and it is the source of the elements identified in chemical analyses. This is true of both the large or clastic grains and smaller grains, and also of the clay minerals. In the case of compositional characterization for provenience, mineralogical examination will usually indicate whether chemical analysis is necessary, and if so, what kind and of which specimens (see Artioli 2010: 232; Stoltman 2001: 298, 322). Moving from low- to high-tech enables a constant interaction between successive levels of analysis and selection of sherds for additional study, always using earlier findings as guidelines for later procedures.

· Remember Remnant Properties.

The analyzed characteristics of archaeological pottery are remnant properties remaining hundreds or thousands of years after manufacture and use. Thus the physical, mechanical, thermal, and compositional properties and performance characteristics of an excavated sherd may be different from those of the original pot. In the many years between manufacture of a vessel and recovery of its remaining fragments, varied processes and conditions, largely unknown, affected the vessel during primary use, secondary or recycled use, and burial in the postdepositional environment (Secco et al. 2011). These are particularly likely to have affected low-fired, porous terracottas and earthenwares, compared with higher-fired ceramics. What are measured today, then, are the surviving remnant or residual properties of the material combined with possible added or subtracted phenomena (e.g., rehydrated clay, mineralization from groundwater). Characterization analyses can be used to estimate the ancient parameters but are not necessarily precisely equivalent to them.

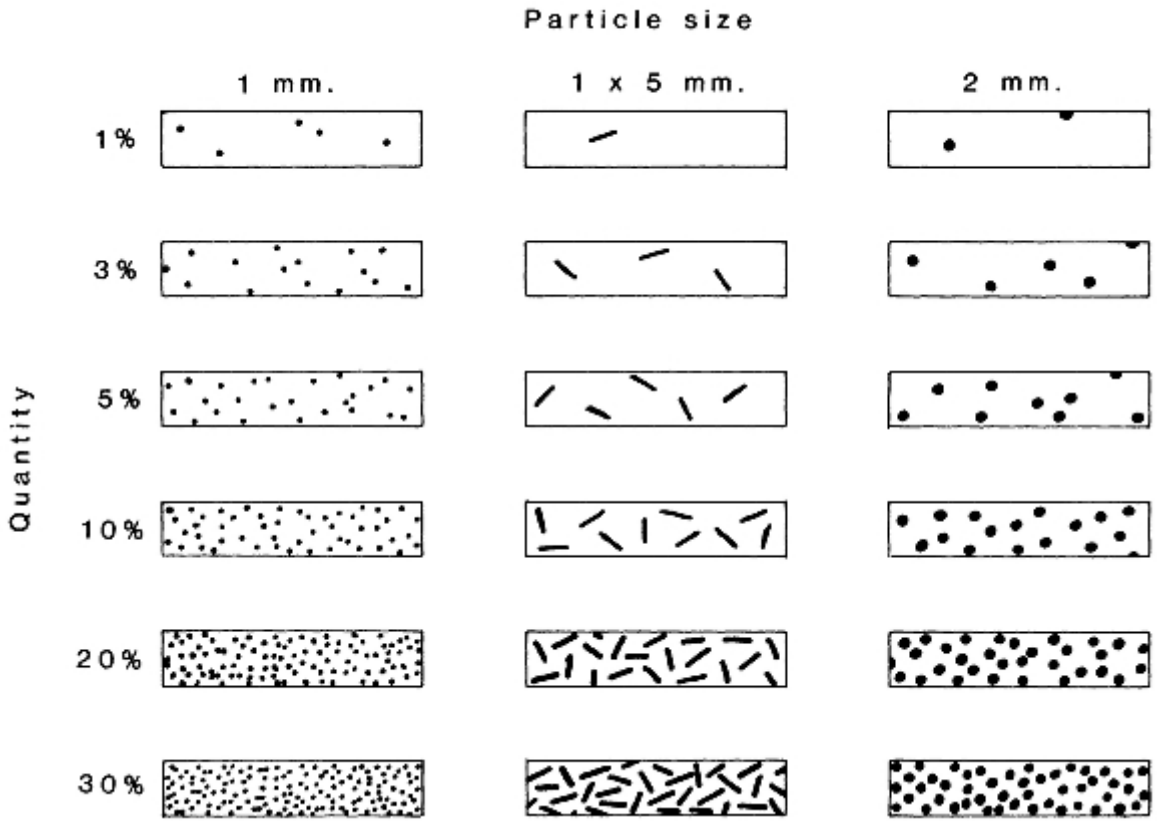

Figure 15.1 Comparison chart for estimating various quantities of different sizes and shapes of particles in a sherd cross-section.

15.2.3 Sampling for Characterization

Given the not insignificant cost of physicochemical analyses, their remarkable sensitivity to infinitesimal amounts of particular elements in the specimens, and archaeologists' concerns about sampling in general, it is surprising that there are relatively few discussions of sampling sherd collections or clays for these purposes (Bishop et al. 1982: 278–81; Neff 1993; Rye 1981: 6–8, 12–13; Shackley 1975: 23–36). Physicochemical analyses may be a significant component of an archaeological field project or they may be undertaken at a later stage of analysis of a collection of artifacts. Regardless, many of the same preliminaries apply, but in a more specific manner.

Box 15.2 Quick Methods of Mineral Identification

Several relatively simple techniques can show the presence of specific minerals in a clay or fired ceramic (see, e.g., Peacock 1977: 30–32, for a key to identification of inclusions). These are generally nonquantitative, however, and therefore indicate only presence/absence.

- Montmorillonite clays, if allowed to rest five minutes in a saturated aqueous solution of benzidine, will turn blue (Shepard 1976: 153).
- If a clay or sherd is crushed and sieved, individual mineral grains may be separated and identified by characteristic properties such as luster, color, and cleavage, familiar to mineralogists and listed in most mineral texts (e.g., Mason and Berry 1968).
- The characteristic colored streak left on a white porcelain "streak plate" will identify certain minerals such as hematite (red streak) or limonite (yellow streak).
- Particles of magnetite will adhere to a magnet moved over the sample grains.
- Carbonates in raw or fired (at less than 750°C) clays are easily identified by their characteristic dissolution and effervescence when acid is added. Hydrochloric acid at room temperature will make calcium carbonate (limestone or calcite) in a clay or sherd effervesce, and magnesium carbonate (dolomite) effervesces in warm hydrochloric acid.
- Staining can be an aid to identifying carbonate minerals in hand specimens or thin sections (Dickson 1966). An organic reagent, titan yellow, can be added to determine the presence of magnesium: with only 5% or more magnesium in the material, the solution turns pink, whereas if only calcium is present the solution remains yellow (Shepard 1976: 381).
- A similar staining technique can be used to distinguish feldspars of different compositions (Bailey and Stevens 1960).
- If the presence of salt (NaCl) is of interest, a sherd may be soaked in small amounts of distilled water for 24 hours and then removed. A few drops of silver nitrate ($AgNO_3$) added to the water will form a white precipitate of AgCl if salt was leached from the sherd, making the water cloudy. The addition of salt to a clay before firing cannot be determined by this method if the pottery was fired to 800°C, because at that temperature the salt reacts with other constituents and at higher temperatures chlorine volatilizes.

15.2.3.1 Research Question: The Basics

Analysis must begin, of course, with a research question or problem to be answered or solved and selection of appropriate attributes or variables, but for characterization purposes these are phrased somewhat differently.

- First: What kind of characterization, what kind of information about the ceramic, is needed? Mineral or chemical constituents? Physical, mechanical, or thermal properties?
- A close second: What part of the ceramic is of interest? The body or paste of the object, or its surface?
- If the body is of primary interest, are the questions about general or bulk composition, or about individual inclusions (point analysis), or about particular phases (e.g., porosity)?
- If interest is primarily in the surface, is it in constituents or properties of the slip (e.g., permeability) or glaze? For glazes, usually only element determinations are made. Is it in paint composition (a point analysis)? Is it in physical, mechanical, or thermal properties related to surface treatments? Postdepositional alteration?
- Third: Is quantitative (actual amount) or qualitative (presence/absence; more or less) characterization needed?

Many concerns center on sample preparation and the specific sample requirements of different methods. For example, who does the sample preparation, and are special techniques or equipment necessary? Complex questions surround the degree of destructiveness of the method's sample requirement, which is of particular concern for rare or whole objects, especially if they are of exhibit quality. Techniques range from requiring no sample removal to completely destructive. In the former, the analytical apparatus is external to the object: X-ray fluorescence, particularly the new portable devices, can analyze very small artifacts without removing a sample, and PIXE can be used even on large and bulky objects. New X-ray tomography (or micro-computed tomography) technology will doubtless prove useful for studying pottery (e.g., Kahl and Ramminger 2012) and other archaeological materials. Destructive methods require removal of a sample which is completely consumed or rendered unusable after the analysis (Chiari 2010: 119). Many techniques may be considered semi-destructive.

Techniques for examining physical properties, such as strength or porosity, and refiring tests require fairly large (and sometimes multiple) samples of standard size cut from the sherd, and such damage may preclude application to any but the most expendable of undecorated wares. Techniques of mineral and chemical analysis vary greatly in the amount of material needed, and consequently the amount of damage done to the sherd or vessel. Petrographic thin-sectioning requires removing a rather large slice of the vessel, usually several millimeters thick and 1–3 cm long, typically by cutting with a diamond saw. Once the section is prepared, however, it can be retained as a permanent record of the ceramic and examined repeatedly. Heavy mineral analysis requires crushing several grams of the ceramic and separating various mineral fractions. Many chemical methods require that a sample be removed from the specimen. In choosing a characterization technique, then, it is important to know whether a sample must be removed from a sherd, how much material is required, and whether it is destroyed or can be reused in other analyses.

15.2.3.2 Considering Methods

Answers to the above questions help determine which general category of methods to use—chemical analyses, mineral analyses, or materials engineering tests—and also begin to reduce the options. Deciding on a method requires different considerations that help narrow the choices to techniques appropriate to both sample constraints and research objectives. Thus for each method used or contemplated, and for each sample to be analyzed, the following issues and questions should be addressed:

- What is the sensitivity of the instrument? What minerals or elements can be reliably detected and at what level?
- What is the accuracy of the instrument in quantitative analyses? How are ambiguities resolved? What kinds of standards and calibrations are used?
- What are the limitations of the technique (in sample size, elements analyzable, accuracy, etc.)?

- What is the cost of the analysis? What is the cost per sample? Do charges include the use of the instrument, the operator's time, sample preparation, data reduction, and extra analyses for clarification or resolution, should they be necessary?
- How much time is involved? How long does it take to analyze one sample? The entire data set? How long until final results will be available? Should delays be anticipated?
- Are the instruments available and in optimum working condition to perform the analyses? Are there experienced operators? What sort of backlog or priority system controls access to the equipment?

Some additional issues will be of greater or lesser relevance depending on whether the analysis will be performed by a specialized or commercial laboratory facility versus "in-house":

- What kinds of data and results are returned? A summary report? Raw data? Are the data given multivariate statistical transformations (if necessary)? Who performs these? Is this charged separately?
- Are the samples or remnants of them returned?
- Are there any intellectual property expectations or restrictions (e.g., on publication, authorship, copyrights, software, data use) associated with the analyses?

15.2.4 Sampling for Chemical Compositional Analysis

Because of the technical precision required to detect and measure elements occurring as a few parts per billion in a larger matrix, problems must be carefully defined, the pottery samples to be analyzed carefully selected, and appropriate methods chosen. It must be remembered that techniques capable of one kind of compositional analysis, bulk or point, cannot always be used for the other. The bulk chemical composition of the body of a ceramic, even an unslipped or unglazed one, cannot be analyzed by a technique that penetrates only a few microns below the surface of the sample, except by preparing a ground powder sample of the body.

For elemental analyses at the trace and ultratrace levels, sherds must be cleaned of contamination on surfaces and edges, usually by scraping with a noncontaminating drill or burr commonly of sapphire, tungsten carbide, or diamond (see Attas et al. 1984; Blackman et al. 1993: 68; Boulanger et al. 2013; Carriveau 1980). The sample to be analyzed may be obtained by crushing a fragment in an agate mortar or by drilling into the core of the sherd with the clean bit of a noncontaminating drill. Important questions concern the amount of the sample to be removed for analysis. Some techniques of chemical analysis, such as INAA, can be performed with only 50 or so micrograms of sample. Drill bits vary in size down to very small diameters, so it is possible to extract small amounts of material even from very thin sherds and inconspicuous areas at the base of exhibit-quality artifacts. It may be advisable to sample sherds in several places to get a more representative selection of material, and to obtain a considerably larger quantity of material than is actually required by the technique. The separate samples may be analyzed individually or mixed and subsampled. One strategy for subsampling is to mix and heap the fine powder into a pile, quarter it, select one quarter, and then repeat this procedure until the material has been reduced to the amount needed.

Although the surfaces of sherds are routinely removed, in environments with high permanent humidity and relatively stable warm temperatures, damp soils and groundwater may have permeated to the interior of porous low-fired pottery. This can affect various analyses and measurements including cation exchange capacity, alteration of iron oxide states, differential thermal analysis, magnetic dating, and firing-temperature determinations. A damp, warm burial environment can also alter the pottery's chemical or mineral content, including rehydration of clay minerals (see Courtois 1976; Franklin and Vitali 1985; Freestone et al. 1985). This could be a problem in situations where extensive leaching, corrosion, or other alteration of the ceramic surface may have occurred in the depositional environment (see Courtois 1976; Franklin and Vitali 1985; Freestone et al. 1985; Hancock 1985; Golitko et al. 2012). Postdepositional alteration may be recognized in thin section as diagenetic changes in minerals, such as carbonate or phosphorus deposition, which may affect XRD.

One obvious concern at every stage, especially for analyses of chemical elements present in amounts as tiny as parts per million or billion, is that care must be taken to avoid contamination of any sort. The analytical techniques that measure chemical elements in such amounts are extremely sensitive to slight compositional variations caused by contaminants or careless sampling. As a result, it is critical that the differences determined for the sherds reflect real differences in raw materials and not errors introduced during sample preparation.

At the same time, it must be remembered that no sherd (or rock) is of uniform composition: natural inhomogeneities are present in the raw material and in the final product. If a particular sherd or clay were sampled and analyzed repeatedly, the determined quantities of chemical elements it contains would vary owing to both "natural" or geochemical causes and statistically random variations in counting and detection. Thus the chemical composition of any one sherd of a particular type of pottery made from a particular resource or combination of resources can be expected to differ slightly from that of another sherd of the same type and raw material(s); but the composition will also vary among samples taken from a single sherd. These concerns are routinely incorporated into the statistical transformations of compositional datasets.

This variability is a particular problem with sampling coarse-textured pottery. Although chemical methods such as INAA give extremely sensitive and thorough analyses of the trace constituents of the material, they provide no data on how the elements are distributed, or on the structure of the fabric. Internal variability is likely unimportant with extremely fine pastes, but it certainly is salient with coarse-textured, low-fired pottery. Mineral inhomogeneities—in kind, grain size, and abundance—and the lack of vitrification can make representative chemical sampling a serious concern.

A look at some of the literature on sampling rocks and particulate matter for chemical analysis reveals less emphasis on the frequency of the clastics and more on grain size: sample size is determined by average grain size (e.g., Bromund et al. 1976; DeBruin et al. 1976; Kleeman 1967; Reeves and Brooks 1978: 5–6; Shackley 1975: 24–25; Shotton

and Hendry 1979: 82). The larger the average (sometimes the maximum) size of the grains in the material to be analyzed, the larger the sample must be to represent the whole—a tiny amount might register chemical aberrancies such as unusual grains that would not reflect the overall composition. The general rule of thumb of sampling collections—the more heterogeneous the population, the larger the sample required for representativeness—holds true for single sherds as well: the heterogeneous kinds and sizes of grains in the paste can be considered analogous to the variability in a population. It has been estimated that samples on the order of several hundred grams to several kilograms (Reeves and Brooks 1978: 5), ground and subsampled, may be necessary for representative analysis of rocks. The situation with coarse, low-fired traditional pottery is not dissimilar, and it may be necessary to analyze both more and larger samples to obtain a reasonably accurate indication of compositional variation. All this provides further justification for beginning compositional characterization studies of pottery with mineral analyses.

16 Color

> Colors are, in practice, semiotic codes. Everywhere, both as terms and concrete properties, colors are engaged as signs in vast schemes of social relations.
>
> Sahlins 1976: 3

Descriptions, analyses, and classifications of pottery, whether complete vessels or vessel fragments, frequently use the color of the fired clay body or its decorative surface treatments as a key variable in discriminating categories. These categories are then assigned some significance in cultural, temporal, or technological terms. Color is one property that permits easy visual differentiation and it is important in technical as well as aesthetic senses, for the color of a ceramic body can tell us about the raw materials used and the way it was fired.

16.1 Human Perception of Color

Color is not an inherent property of an object but a function of the light from it that reaches the human eye. What the eye perceives as color is a form of electromagnetic energy traveling within a certain range of vibration rates. This range, known as the visible spectrum, includes wavelengths of 400 (violet) to 700 (red) micrometers (fig. 16.1). Vibrations beyond this range, such as microwaves and radio waves, cannot be seen, nor can shorter waves of electromagnetic energy such as X-rays or gamma rays. Objects that appear transparent, such as glass and glazes, are registered by the color (energy) of the light that passes through them, whereas opaque objects are seen as the color of the light reflected, all other wavelengths being absorbed.

The perception of color may be linked, consciously or unconsciously, to attributes independent of electromagnetic energy, as is evident in efforts to elicit folk classifications or measurements of colors. For example, Mexican potters could not match clay colors with standard charts (the Munsell Color Charts) because the latter "lacked the features of wetness, texture, and smell that they considered essential in judging 'color'" (Kaplan 1985: 358). The use of color on pottery (and other categories of material culture) often highlights fundamental aspects of the structure of belief or worldview of a people. For example, in Puebla, Mexico, distinctions between red and black colors in general—red associated with life, day, and hot and black with death, night, and cold—are extended to distinctions in the use of the pottery of different colors (Kaplan and Levine 1981: 876–78; for an example from India, see Miller 1985: 142–48).

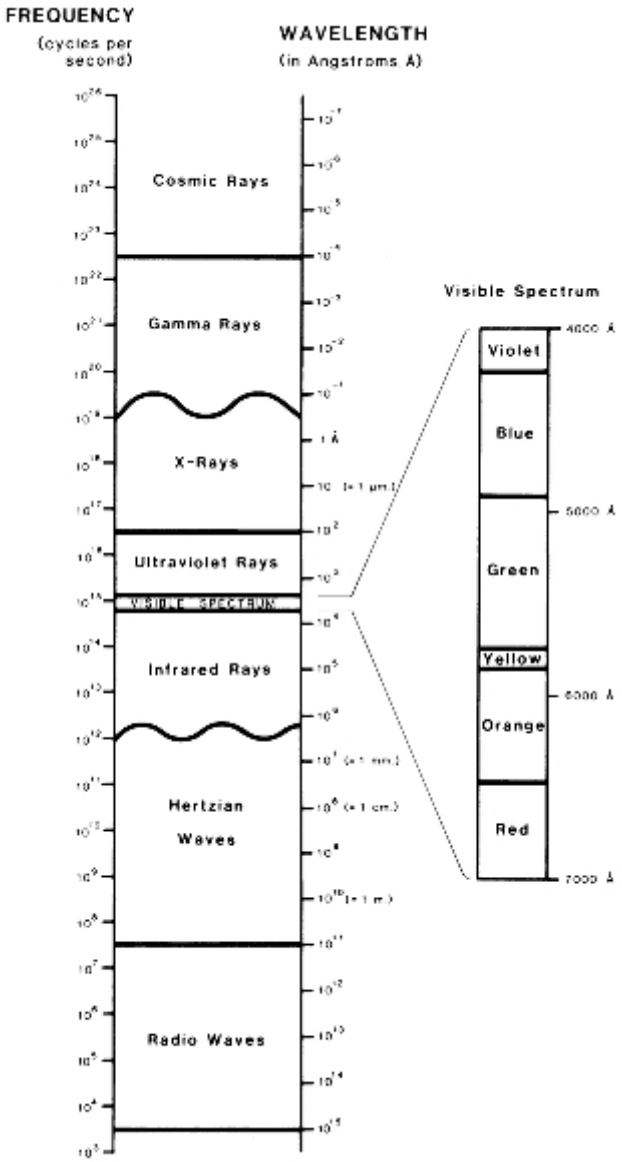

Figure 16.1 The electromagnetic spectrum, divided into regions on the basis of use and mode of detection. The visible spectrum ranges between 4000 and 7000 Ångstrom units (1 Å = 1×10^{-8} cm).

Color variations are often described by terms denoting various degrees of lightness, darkness, or saturation of the color (fig. 16.2):

- Shades are dusky colors created by mixture with black.
- Tints are light, clear colors mixed with white.
- Tones are mixtures of colors plus black or white.

Continuing research by linguists and vision specialists into various contexts of color perception and differentiation has supported two principal generalizations of the "color encoding sequence" developed by Brent Berlin and Paul Kay (1969). One is that most languages share similar divisions of "color space" and the second is that the terms for these divisions evolved linguistically in a similar order. The new model of this phenomenon is based on partition (table 16.1): the "specific tendency for languages to

provide a small set of basic color terms that jointly partition the perceptual color space" (Kay and Maffi 1999: 745). Partitioning occurs through three steps based on primary color appearance. The first two steps consist of separating oppositions, first distinguishing black from white, then recognizing warm (red, yellow) versus cool (blue, green) colors; the third step is isolating red.

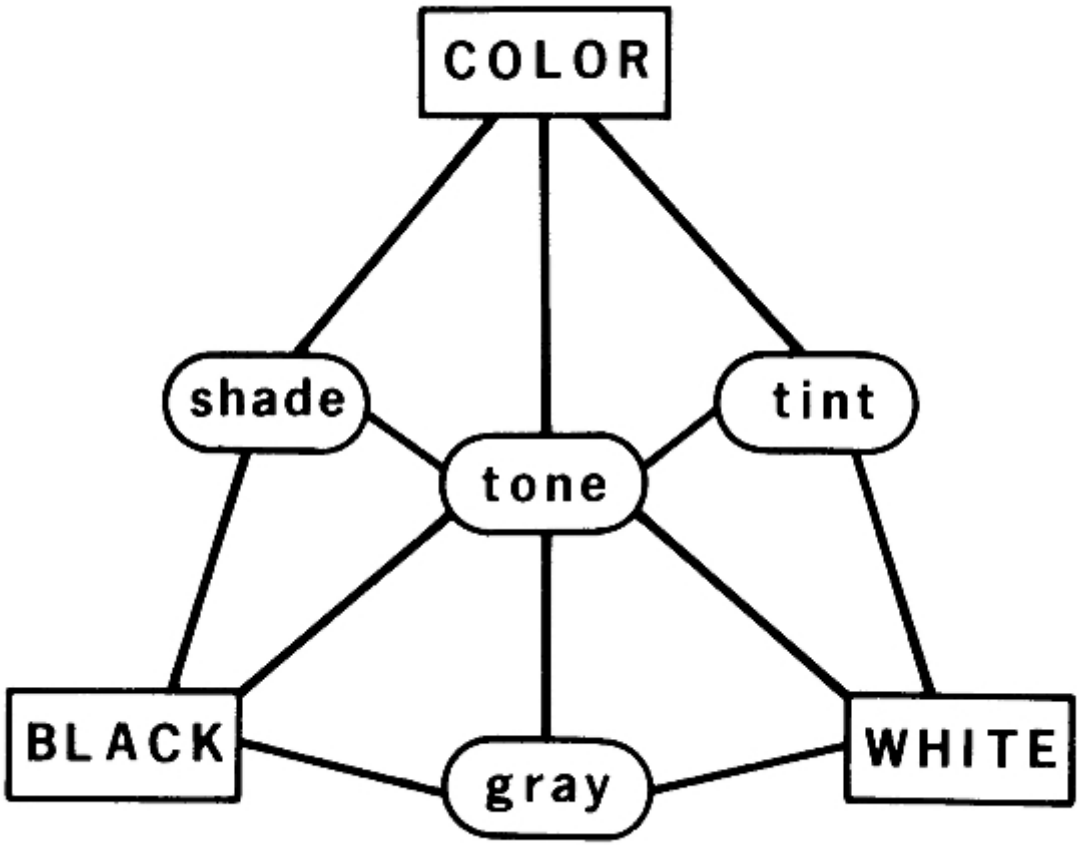

Figure 16.2 Color terms based on mixing with white or black.

This near universal linguistic sequence is thought to have developed along with the salience of the color domain itself in increasingly complex technological systems: "In a technologically simple society, color is a more predictable, hence less informative, property of things than in a technologically complex one. . . . As the colors of artifacts become increasingly subject to deliberate manipulation, color becomes an increasingly important dimension for distinguishing things and hence for distinguishing them in discourse" (Kay and Maffi 1999: 746). It should be noted that this sequence refers to the developmental sequence of color terms in languages, not to the use of pigments themselves in various types of artistic expression (see, e.g., Baines 1985: 285). In unglazed pottery decoration, black, white, and red are the most common colors, probably because they are easy to obtain from common minerals or firing procedures and afford pleasant contrasting and complementary effects.

16.2 Sources of Pottery Color and Its Variability

The color of an object of fired clay is a product of several variables, of which two are most important:

- Impurities: The size, amount, and distribution in the raw clay of impurities, chiefly iron and organic material, that act as colorants; and
- Firing: The time, temperature, and atmosphere of firing.

In general, raw clay color is not a simple or accurate predictor of fired clay color. In an unfired clay, the kind and amount of organic matter and iron compounds (and their oxidation state) determine its color. If a raw clay is free of these impurities, it will usually be light-colored (white or cream) and will probably oxidize to a white to very pale tan color in firing (see Beck 2006a). Raw clays in a wide range of colors including gray, bluish, brown, or black likely contain organic matter and/or iron and may fire to cream, brown, or red. The complex interrelations between the color of a fired clay and the color of the original raw material can be seen in table 16.2.

Table 16.1 The "Color Encoding Sequence," Showing the Basic Color Categories Perceived by Humans and the Order in which Specific Terms for These Categories Develop in Most Languages

Stage I	Stage II	Stage III	Stage IV	Stage V
Black	Cool Colors: Black/Blue/Green	Black	Black	Black
		Blue/Green	Blue/Green	Blue
				Green
White	Warm Colors: White/Red/Yellow	White	White	White
		Red/Yellow	Red	Red
			Yellow	Yellow

Source: After Kay and Maffi 1999: 745.

Table 16.2 Relation between Fired and Unfired Colors of Clays

Fired Color	Raw Color
White	White, gray, black
Light brown ("buff")	Cream, yellow, gray, black, brown, gray-brown
Red, brown	Yellow, red, brown, gray, black
Dark gray, black	All colors

Source: After Shepard 1976: 17.

The primary determinant of the final color of a low-fired clay is the presence of iron, but this element does not begin to play an active role until any organic matter present in the clay has been oxidized and eliminated. Thus the atmosphere of firing has a great effect on color development through the abundance or scarcity of oxygen.

16.2.1 Organic Matter

The firing conditions necessary to burn out carbonaceous material vary, depending on the clay mineral species, the amount of organics originally present, and the fineness and porosity of the clay body. A fully oxidizing atmosphere will allow organic material to begin to burn out of a clay at low temperatures, but the rate at which it oxidizes is a function of the fineness of the fabric and the clay mineral composition: a coarse body will lose small quantities even in relatively rapid, low-temperature firings, whereas a fine smectite clay with large amounts of organic matter may retain some carbon coring even after oxidation firing to 800°C.

Significant quantities of carbonaceous matter in a fired clay piece are usually signaled by a dark core in a freshly broken cross section through the wall (fig. 16.3). The presence of a dark core can result from large amounts of organics originally present in the raw clay, or from deposition of carbon during firing, or from some combination of the two. Note that this dark core should not be confused with the black coring noted in high-fired bricks, in which rapid firing leads to vitrification and pores on the surfaces close before the organic material on the interiors has burned out. The gases from these organics as well as other impurities can lead to bloating (Kingery et al. 1976: 503–4).

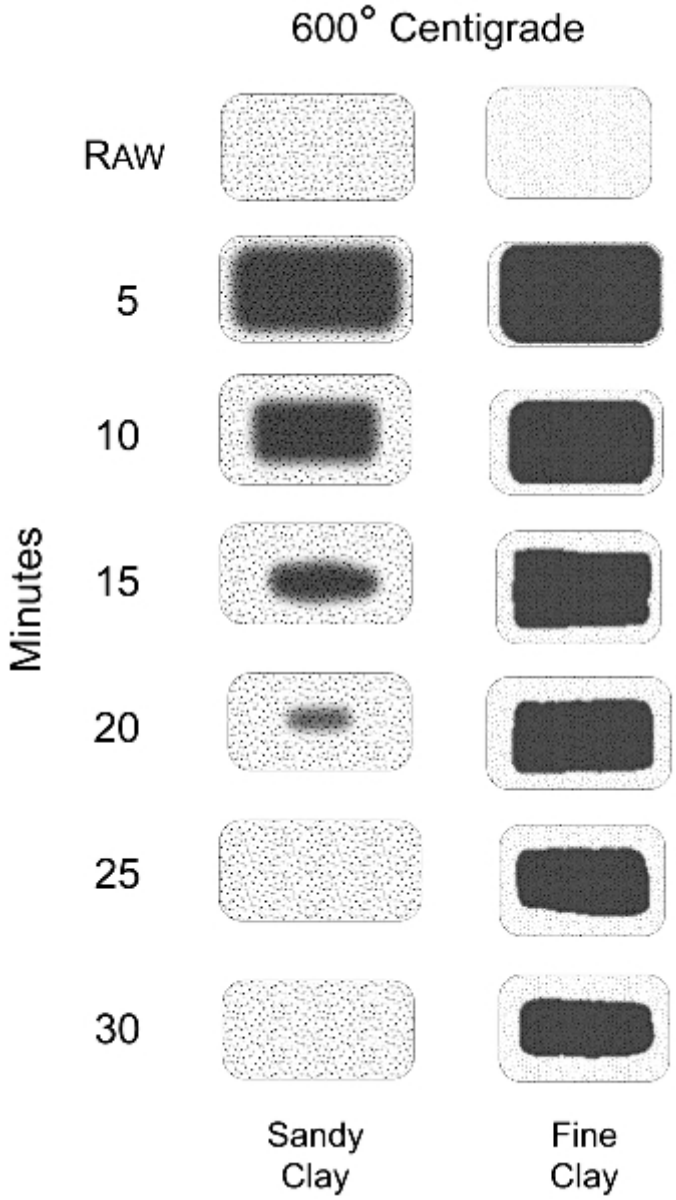

Figure 16.3 Comparison of dark cores in cross-sections of briquettes formed from coarse and fine clays and fired to 600°C for the times indicated. Drawn by Don S. Rice from Matson 1971: plate XXXVb.

A dark core in the center of the cross-section, with lighter colors underlying the surfaces, as in figure 16.3, usually means that organic material was present in the raw clay but was not completely removed in firing. In other words, the conditions of firing —the duration, temperature, and atmosphere—were not such that the carbon could be completely oxidized and eliminated from the clay. This core may be a thin gray streak, indicating little organic material originally present and/or substantial burnout, or it may be a pronounced black band occupying most of the wall section, indicating a highly organic clay and very little oxidation. Dark cores may have fuzzy, indistinct edges, which are common in coarse, porous clays and reveal the movement of organics through the capillaries. In a fine clay the edges may be sharp.

Sometimes the dark organic matter visible in cross section is present at or just below the surfaces rather than in the center. This feature, especially when combined with a

black surface, may indicate final smudging, resulting in carbon deposition on the surface and in the pores. Multiple darker and lighter layers in the clay cross section reflect fluctuating degrees of oxidation caused by strong variations in the atmosphere during firing.

16.2.2 Iron Compounds

Once the organic matter in a clay has been largely oxidized and eliminated, color development based on oxidation of iron compounds begins. The final fired color depends upon several aspects of the iron—its chemical (oxidation) state, the amount present, and its distribution in the clay—as well as on the conditions of firing.

Iron cannot exist in a fully oxidized state while there is still considerable organic material in the clay. The chemical state of the iron is determinable by Mössbauer spectroscopy. Fully oxidized or ferric iron (e.g., hematite, Fe_2O_3) produces red or reddish brown colors, whereas iron in the ferrous state (as in sulfides, carbonates, and silicates) or ferrous-ferric state (magnetite, Fe_3O_4) occurs more rarely and produces gray, bluish, greenish, or gray-brown (see Hess and Perlman 1974). Full color development of iron in an oxidizing atmosphere occurs with increasing temperature of firing up to approximately 900–950°C.

With respect to the amount of iron compounds present in a fired clay, in general, other things being equal, iron oxides in amounts of 1% will contribute a yellowish tone to the fired clay, 1.5–3% will cause light brown or orange, and 3% or more red (Shepard 1976: 150). The distribution of the iron is a function of the particle size of the clay. The finer the clay, the greater the surface area and the more finely particulate the iron required to cover this area. In addition, the total amount of iron in a clay may include small nodules of magnetite, pyrite, hematite, or other iron-rich minerals (red or reddish-brown "ferruginous lumps") rather than being evenly distributed as fine particulate matter, and this would affect its contribution to the overall color of the piece. Two clays of nearly the same fired color were discovered to have significantly different quantities of iron: one had 3.12% ferric oxide while the other had 12.4% (Shepard 1976: 16, citing Ries 1927: 260).

At high temperatures iron compounds may act as fluxes, especially when they are finely particulate or are exposed to a reducing or incompletely oxidizing atmosphere. In such situations, the red color may change from red to brown to blackish as the formation of a glassy phase inhibits continued oxidation and has the effect of a reducing atmosphere. An example of this on prehistoric Mesoamerican pottery is the fine ferruginous slip of Plumbate ware, manufactured in southern Guatemala, which has an iridescent gray slip that is partially vitrified (Neff 2003; Neff and Bishop 1988; Shepard 1948a). A similar situation may exist with "Northern Black Polished Ware" of Iron Age India, in which X-ray photoelectron spectroscopy, scanning electron microscopy, and X-ray diffraction showed that the glossy "bronze metallic" black slip

may be due to sintering of an iron-rich biotite layer on the surface (Gillies and Urch 1983: 38–41). The red colors of ferric oxides are generally not stable if fired to temperatures above 1000°C (Norton 1970: 217). Magnetite (Fe_30_4) may be used as a black pigment if it is prevented from oxidizing in firing (Shepard 1976: 39).

16.2.3 Other Colorants

Besides iron and carbon, other constituents such as lime may contribute to the color of fired clays if they are present in significant quantities. These changes usually take place at moderately high temperatures, about 800°C and above. For example, once $CaCO_3$ has decomposed, the CaO may react with clay to form pale yellow or white calcium silicates (wollastonite). At high temperatures, above 1000°C, lime may also react with iron to form calcium ferrosilicates, suppressing the red color and contributing to a yellow or olive-greenish tone.

Manganese may be present as reddish-brown or blackish-brown flecks or nodules in clays, particularly those from swampy areas. It is rarely found in sufficient quantities (ca. 10% or more) as a natural constituent of clays to cause an overall black color in the paste. Nodules or concretions may be ground and mixed with a binder for use as painted decoration, contributing a black, brownish black, or purplish brown color (see Shepard 1976: 40–42). Titanium, present either as TiO_2 or as titanate of iron, may contribute a light tan or cream color in iron-free clays.

Sulfides (pyrites, marcasite), sulfates (gypsum), and chlorides may also influence the color of fired clays. As soluble salts, these materials migrate through the capillaries of the wares as they dry and concentrate on the surfaces, forming a brownish or whitish scum or efflorescence that resembles a white slip after firing. The location of the scum will identify areas of the vessel that were uppermost (exposed to air) in drying and will contrast with surface areas that may have been scraped in further finishing (see Frankin 1971: 236).

Colors such as pure yellow, blue, and green are virtually impossible to achieve with low-fired pottery except by special pigments usually added to high-fired clays or glazes, or applied after firing.

16.3 Measuring Color

Although the wavelengths of the electromagnetic spectrum can be measured by a spectrophotometer or other colorimetry instruments to determine colors precisely, in archaeology pottery colors are most commonly measured or classified against a series of standard samples. Early systems included Robert Ridgway's *Color standards* (1912), consisting of 1115 named colors used to describe the colors of birds, and the Maerz and Paul (1950) *Dictionary of color,* presenting 7000 color samples (see March 1934: 26–27; Colton 1953: 32–36; Shepard 1936: 430–32). The most commonly used standard today is the Munsell color system, developed by Alfred H. Munsell, a Boston artist and art teacher, between 1898 and 1912 (Munsell 1905; Nickerson 1948). This system has been standardized by the American Society for Testing and Materials (D 1535–68 Standard Method of Specifying Color by the Munsell System; https://law.resource.org/pub/us/cfr/ibr/003/astm.d1535.1968.pdf).

In the Munsell (http://munsell.com) system, the range of colors is conceptualized into the three dimensions of cylinder, creating a "color solid" that approximates an irregular cylindrical form (also called a "tree") (fig. 16.4). The central, vertical axis of the color solid is surrounded by individual vertical sections identified by their hues or wavelengths as red, yellow, etc. (fig. 16.5). These sections are further subdivided into individual hue-constant charts that display a series of vertical and horizontal color gradations.

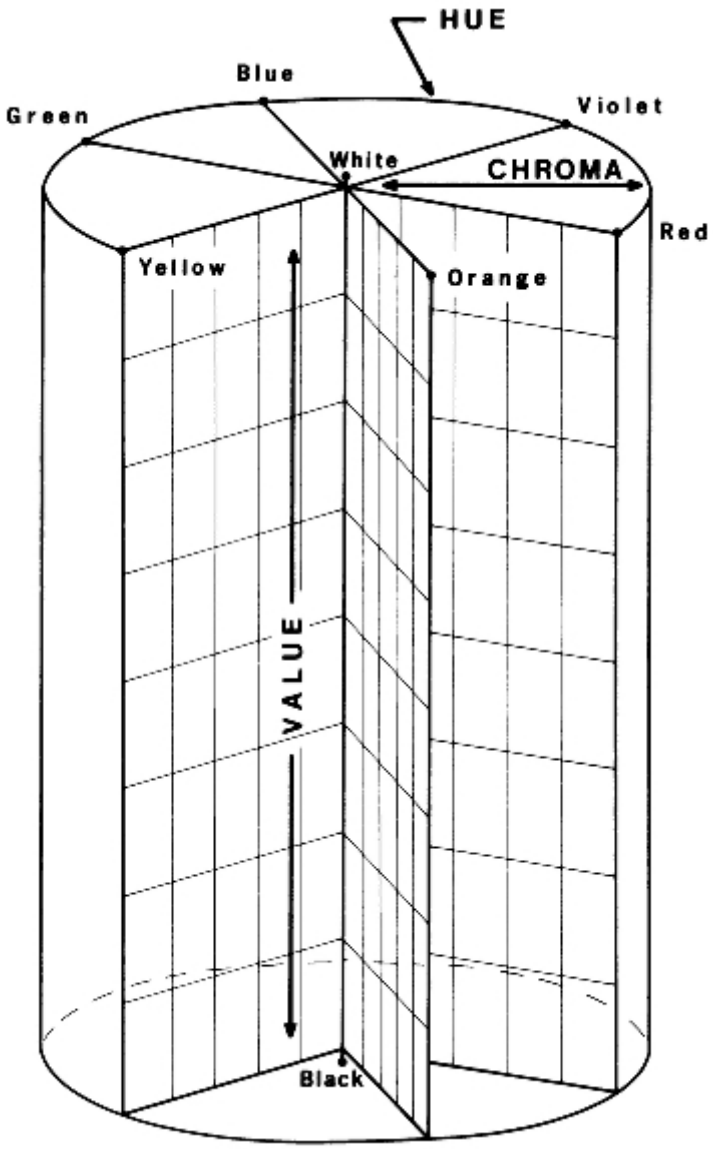

Figure 16.4 Model of a "color solid," simplified into a cylinder, from which the Munsell color charts are drawn.

Stated differently, the Munsell system standardizes color specifications by organizing the variables of color into three graded dimensions, beginning with hue:

- Hue: named colors, the dominant wavelengths in the color spectrum. Hues are the individual charts that extend around the circumference of the solid. Complementary pigment colors (pairs of colors that give neutral grays or black when combined equally) are on opposite sides of the cylinder: blue is opposite orange, red opposite green, and yellow opposite violet.
- Value: intensity, brilliance, or brightness of the hue. Value varies along the vertical dimension of the cylinder, with black and dark colors at the lower end and lighter colors at the upper. The central axis of the figure represents a region of "neutral" colors.
- Chroma: saturation, strength, or purity of the hue. Chroma varies along the radius of the cylinder, from black or gray shades near the central axis to a clear pure color at the exterior "surface."

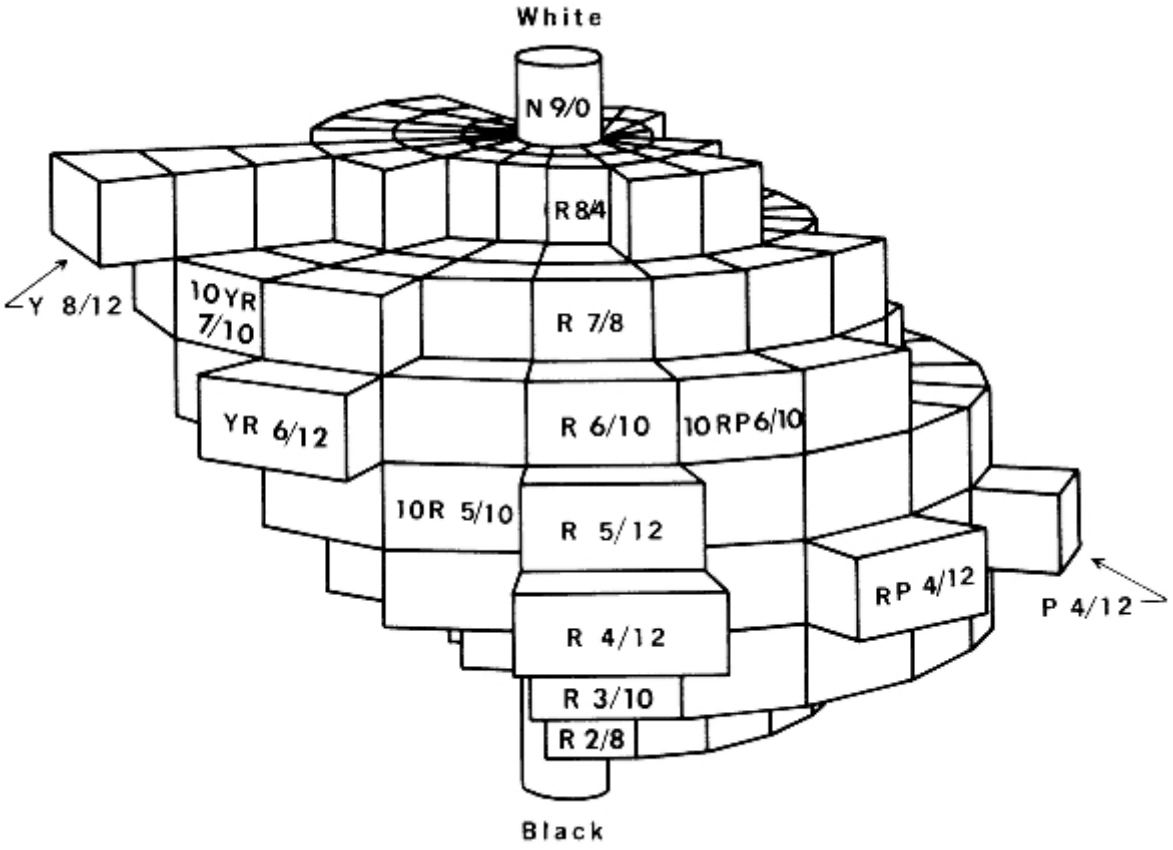

Figure 16.5 Three-dimensional model of the Munsell color system. After Nickerson 1948: fig. 6.

Essentially, all the individual color chips represent color tones, with lighter/whiter/clearer tints near the top and right side of the individual hue charts, and darker/duskier shades in the lower portion and closer to the central axis.

For graphic representation and application, the colors in the Munsell cylinder model are designated by alphanumeric codes. The hue identifier (or page) is given first. Then value and chroma are indicated by numbers from 0 to 10 (or higher), moving bottom to top and left to right. For achromatic colors (black, white, some grays), the designation N (neutral) replaces the hue. For example, the color of a pot coded 5YR 6/8 means the color was found on the 5YR hue sheet, designating a medium reddish yellow. The value or brightness, given next at 6, is medium-high and, separated by a slash, the chroma value of 8 indicates relatively high purity or strength. A color of 5YR 3/4 represents the same hue but is a darker and grayer (browner) shade and tone, lower in value and chroma.

The Munsell charts include virtually all colors in the visible spectrum and can be used to specify colors of any variety of materials, including textiles and paints. For unglazed pottery a portion of the red and yellow spectrum is commonly used. These selected charts are referred to as the Munsell Soil Color Charts and are sold by the Munsell Company as a package for use by scientists interested in classifying the colors of natural soils and earthy products. The soil color package includes the following red-yellow hue pages—10R, 10YR, 2.5Y, 2.5YR, 5Y, 5YR, 7.5YR—plus separate pages

for green, “gley” (bluish grays), and reds (5R and 7.5R). Charts covering clear blues, greens, and yellows are normally not used in unglazed pottery studies, though they are important for identifying the colors of glazes and painted decoration.

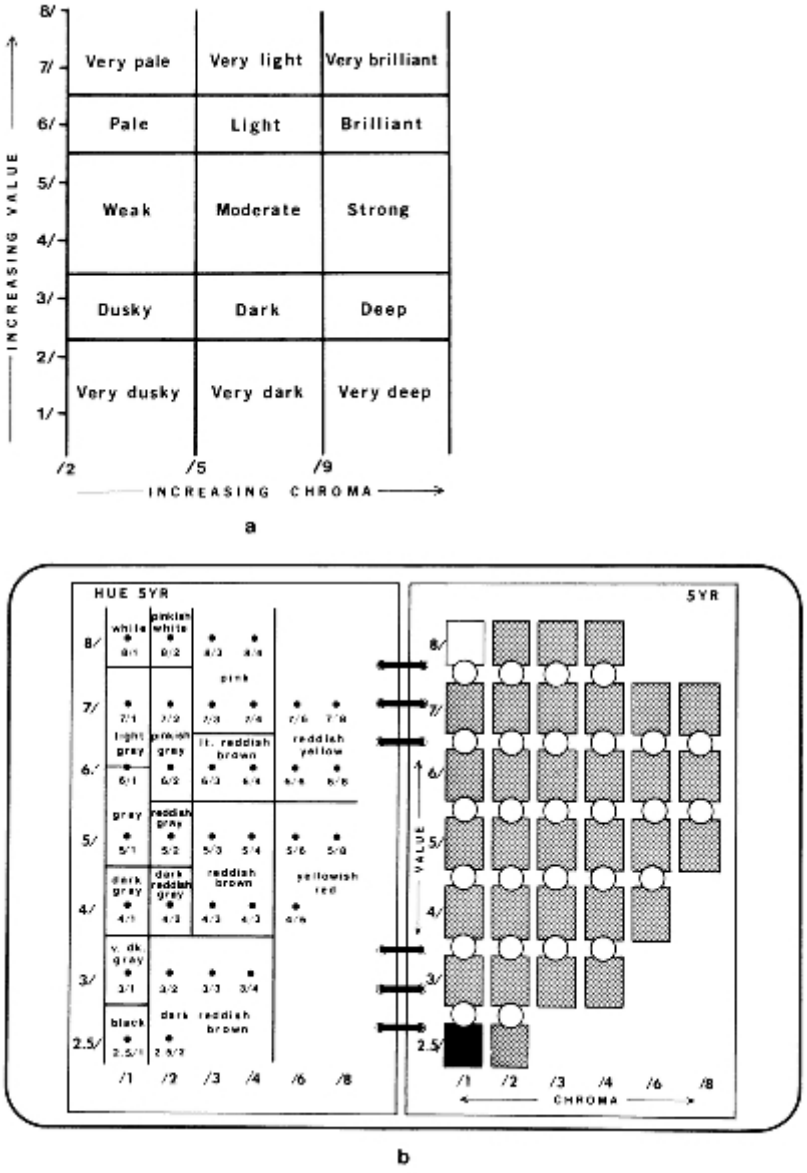

Figure 16.6 The Munsell soil color charts: *a*, a system of modifiers for color names; *b*, the Munsell soil color book opened to hue chart 5YR. *a* shows color chips varying in value and chroma; *b* shows names for the various colors on the chart. Sources: *a*, after Shepard 1976: 110; *b*, after Munsell Color Company 1975.

Box 16.1 Reporting Color Measurements

Recorded or published Munsell Soil Color Chart measurements should include both the alphanumeric notation and the verbal description. In some instances the Munsell verbal category is unsatisfactory; for example, a wide range of visually distinguishable colors is called "yellowish red" or "very pale brown." It is likely that in these situations more information on the actual color will be conveyed by using nonstandard but commonplace terms such as orange, cream, and so forth. The term "buff" is not recommended, because there is a wide variation in the actual colors (from tan to brownish to pale yellow-orange to cream) denoted by this vague adjective. In some areas such as the Southwest United States, however, this term has a long history of use and the color may have many causes, including surface scumming (see Beck 2006a).

Often an exact match cannot be found between a specimen and the Munsell soil charts because of the gaps in specific hue, chroma, and value illustrations on each chart. In such situations, more specific designations are attained by interpolation with decimals, usually by distinguishing the approximate value and chroma positions on one hue chart. For example, a color may be found to be 10YR 7.5/4.5 by interpolating between values of 7 and 8 and chroma of 4 and 5 on the 10YR chart. It may sometimes be necessary to interpolate between hues—for example, 9YR 7.5/4.5. Reliable interpolations smaller than a half-step (0.5) between illustrated chromas and values are difficult to achieve and not recommended.

In conducting a series of color measurements on a pottery collection, it is important that all measurements be made by the same person to eliminate individual variations ("operator error") in color perception. In addition, all measurements should be made under the same lighting, with light hitting the specimens and the color chips at the same angle. The quality of the light can cause variations in the color readings, but these can be minimized if the conditions are standardized—for example, if all recordings are made in the same room. Lighting conditions in the field may be less than satisfactory, but direct sunlight should be avoided. In reporting color measurements, the lighting at the time of measurement should be noted. Munsell packages usually come with page-sized cards of gray and black cardboard with windows cut out of the centers. These can be used to mask out the confusion of multiple colors when trying to decide the best match between pairs of values and chromas.

Ideally, color measurements should be made on both exterior and interior surfaces of a sherd or vessel, as well as on a freshly broken cross section. In the cross section, the presence and thickness of any dark coring should also be noted. For large collections it is generally most informative to record both the typical color or color range of the material and the extreme variations in hue, value, or chroma. This is also important because of the variations in surface colors resulting from non-kiln firing. Thus the color of a particular category of pottery might be reported as "5YR 7/6, varying to 5/4, 8/7; 7.5YR 6/5."

Besides the alphanumeric codes, the Munsell charts give verbal color names and modifiers for specific description of the hues (e.g., see fig. 16.6*b*). Although these terms are not highly evocative, they are, in combination with the notations, preferable to the descriptive terms used formerly, which in Mesoamerican ceramics included dubious descriptors such as "Mouse Brown," "Avellaneous," and "Vinaceous Tawny" in the Ridgway system.

16.4 What Are Color Measurements Used For?

Color measurements are a relatively routine part of raw data recording on pottery for descriptive and classificatory purposes and these are useful comparatively. Description of pottery colors by means of objective and widely available standards, such as Munsell charts, facilitates the objectives of comparisons of types and assemblages, and thus aids in inferences of dates and trade relations.

Munsell measurements provide four data points on ordinal (ranked) scales: two on hue, plus value and chroma. These observations should, in principle, be useful for something beyond description but there has been little exploration of this possibility. For example, color measurements can be an aid to interpreting the original firing conditions of low-fired pottery as evidenced in relative degrees of oxidation of carbon and iron. For such interpretations, it is useful to analyze separately the variations in value, chroma, and hue within a given type or collection, because each dimension tells something different about the original clay and the firing conditions.

Does the greatest variability occur in hue or in chroma or in value? Low numerical codes for value and chroma hint at the amount of free carbon present in the sherds. Although this alone does not tell whether the carbon was initially present or deposited during firing, the presence of a dark gray (low chroma and value) color indicates incomplete oxidation: either an atmosphere with insufficient oxygen or a short period and/or low temperatures of firing. By contrast, higher value and chroma designations indicate greater oxidation, less organic matter initially present in the clay, or both. Chroma is more apt to reflect the increasing development of the color of whatever iron is present, although of course the relative amounts of iron are primarily indicated by the hue designation. Chroma varies with the breakdown of clay minerals at temperatures beyond 850°C, and a change in hue from Y to R may reflect the degree to which limonite is dehydrated to hematite (Hodges 1976: 196). These are approximations rather than precise estimates with respect to firing time, temperature, and atmosphere, however, and a number of more precise techniques are available for determining firing temperature in particular (see chap. 23).

Two studies suggest the possibility of close relations between color and paste composition. Fragments of compositionally analyzed pottery from the Classic Maya site of Palenque were refired and their hue, value, and chroma measurements taken (Rands and Bargielski Weimer 1992). Hue and value measurements were found to correlate generally with compositional groupings, although chroma (saturation) was of little interpretive use.

Box 16.2 Experimental Firing and Refiring

Laboratory firing experiments with local clays are usually conducted in electric kilns in a fully oxidizing atmosphere. Draw trials (removing test tiles or briquettes at a series of increasing time and temperature intervals) will establish the relation of firing time and temperature to a variety of use-related physical properties including color development, shrinkage, weight loss, hardness, porosity, dark coring, and so forth. An alternative strategy is based on a thermal gradient furnace (Matson 1975), which raises the temperature continuously along a gradient from front to back of the kiln in a single firing rather than in a series of independent steps in multiple firings.

Regardless of which procedure is used, firing local clays (with or without various tempers) provides a view of the range of colors attainable (e.g., whether the clays are primarily red- or white-firing) and their development, mechanical properties, and refractoriness or tendency to vitrify at relatively low temperatures. This provides a background for comparing the colors of prehistoric pottery, within which the prehistoric firing strategies can be interpreted (Beck 2006a; see also Matson 1971; Rye 1976: 123–26).

Interpretation of original firing conditions is also aided by refiring fragments of sherds in an oxidizing atmosphere at a series of temperature intervals (e.g., intervals of 100°C) or at a single sufficiently high temperature and duration that most of the organic material can be eliminated and the colors from any iron allowed to develop fully (see Box 23.1). Thirty minutes soaking at a temperature of 800°C or 850°C is usually satisfactory.

Color measurements on a Bronze Age red ware from Cyprus were intercompared on the principle that variability in the different dimensions of color can inform on the degree of technological control (quality control) or culturally acceptable limits (Frankel 1994). The range and proportional occurrences of hue, value, and chroma readings on this material from three sites were graphically displayed and compared with other attributes of the pottery. Clear differences in color were most evident in comparing coarse and hard fabrics against those that were fine and "soft," with some distinctions also noted with respect to calcareous versus noncalcareous pastes. Sample size played a role in the number of colors noted, but interior and exterior colors did not vary significantly.

It is also important that color comparisons be based on sherds that either are from the same ware or represent the same or similar clays, because variations in quantities of impurities affect color development. Two strategies are appropriate in this regard: laboratory firing experiments carried out on clays collected from the locale of interest and refiring experiments with fragments broken from sherds of the ancient pottery.

Refiring samples of sherds of a large variety of wares (whether different pastes, forms, or decorative categories) establishes a general picture of the variability in the kinds of clays the potters used: Did they select primarily red-, brown-, or white-firing clays, for example? Once this is known, other questions can be investigated (see Shepard 1976: 104–7) that are of interest in technological choice and style models. Were particular kinds of clays selected for different forms or decorative categories? Were different firing practices used for different categories of wares? For example, if two kinds of pottery are brown, is this because the same clay or the same firing was used for both, or was one incompletely oxidized while the other naturally attained a

brown color with full oxidation? Is a dark core easily removed, or is it retained after refiring? Some of these relationships are summarized in table 16.3.

Table 16.3 Relation between Fired Color and Original Firing Conditions

Color			
Surface	**Core**	**Probable Firing**	**Comment**
Clear colors; identical throughout cross section		Relatively well oxidized	No evidence of original state of the clay with respect to carbon content; any color development is due to the presence of iron.
Brown	Brown	Incompletely to relatively well oxidized	May be lightly smoked or smudged paste, or color may be due to iron in ferric state. Refiring in oxidation will clear colors.
Clear or light gray	Light to dark gray	Incomplete oxidation	Probably a carbonaceous clay that was not sufficiently fired to oxidize organics and allow color development of any iron present. Refire.
Light gray	Light gray	Incomplete oxidation or reduction	. . .
Dark gray or black	Dark gray or black	Reduced or smudged	May be highly carbonaceous clay or heavily smudged.
Dark gray or black	Light gray	Smudged	Carbon deposited on surfaces during or at the end of firing; lighter core indicates it was not an organic clay. Refiring may clarify colors.
White	White	Uncertain	May be clay lacking both iron and organics. Refire in oxidation to note color development, if any.

Although a range of interpretations may be suggested by color measurements and assessment of changes in color with refiring, these must be understood within the context of the firing technology, which for non-kiln firings is highly variable. Because of non-uniform rates of heating caused by kinds and placement of fuel and by drafts, the colors of vessels from a single load are apt to vary considerably according to the temperatures to which they were subjected. Thus, on the one hand, it could be argued that standard measurement of color of non–kiln-fired sherds represents false precision, because the original conditions through which the colors were developed were uncontrolled and highly variable. On the other hand, careful investigation of the dimensions of that variability can be informative about firing practices in antiquity.

Finally, it is important to note the possible sources of color alteration during use and in the postdepositional environment. Pottery vessels used in or over cooking fires are exposed to smoke, soot, and charring, which deposit carbon on the surfaces and in the exterior pores. Pots used for storage or transport may be stained or build up residues,

such as salts, depending on the substance stored, and processing activities may abrade and discolor the slip, decoration, or surface finish. Post-use or postdeposition processes may alter the color of vessels: accidental burning in house or field fires can oxidize pots or deposit carbon; acid soils and contact with rootlets can cause leaching or staining; and soluble salts or carbonates in the burial environment may leave encrustations or effloresences of a white scum on the surfaces.

17 Mineral and Chemical Composition

> The petrographic and NAA results are complementary to the understanding of the ceramic technological practices. . . . Each technique recognized patterns, but identified different forms of ceramic variation. The compositional and petrographic groups do not necessarily coincide. Some chemical groups have a mineralogical explanation, while others do not. Combining these two lines of evidence clearly provides a better interpretation than considering each result on its own.
>
> Falabella et al. 2013: 44

Compositional characterization studies of pottery should ideally incorporate both mineralogical and chemical methods. Each method and dataset complements the other, the one yielding information the other cannot provide because they vary in the components they are able to identify and measure (Neff 2012). Mineralogical analysis should precede chemical analysis to help define sample selection for the latter (see Artioli 2010: 232; Stoltman 2001: 298, 322). These procedures are typically used in provenience analyses of pottery (sec. 20.2).

As with all types of measurements, qualitative and quantitative, individual analytical methods may be evaluated by several important criteria. These usually refer to errors occurring with repeated measurement (e.g., Artioli 2010: 128–29; Bishop et al. 1982: 289–90; Orphanides 1985):

- Sensitivity: the limits of detection of an elemental-analytical technique. Although sensitivity is usually expressed in terms of the ability to reliably detect relative quantities of minor, trace, or ultratrace components, it may also be expressed as the lowest atomic numbers of elements that can be analyzed.
- Precision: the reproducibility of the analytic procedures in the sense of the closeness of repeated measurements. It can be thought of as distribution about a mean, analogous to the standard deviation in statistics.
- Reliability: the consistency or replicability of a test or analysis, in the sense of avoiding (or revealing) significant errors or outliers. Reliability is closely related to precision.
- Accuracy: how close the result is to the true value. Primarily of concern in quantitative determinations, accuracy depends, among other things, on the calibration of the experimental instruments with reference standards and their compositions.
- Validity: the usefulness of a measurement, or inferences from it, in actually measuring the property it is supposed to measure—for example, if tested by another procedure. Validity is closely related to accuracy.

Accuracy and precision are often expressed as percentages, stating that the measurement of a particular element or set of elements by a given technique is accurate, for example, within ±5%. A technique may be highly sensitive, precise, and reliable, but yet have low accuracy and validity.

These and related issues about the most appropriate techniques to address a particular research problem are best explored in consultation with a physicist, chemist, geologist, or materials scientist well trained in the analytical procedures and capabilities of the techniques of interest.

17.1 Mineral Analysis

Mineralogical analysis of pottery is oriented toward qualitative and quantitative description of the coarser crystalline particles as well as the clay mineral constituents. Typically the focus is on the former, which may be naturally present in the clay or added as temper. Not only the identity of these added minerals but also their physical characteristics (grain sizes, shapes), quantities or proportions, and associations may be important. Identifying the specific clay mineral or minerals composing the matrix generally requires more complicated instruments and entails a narrower range of conditions for making such determinations.

Although minerals can be identified by many attributes, the techniques used in pottery studies ultimately depend on properties determined by their atomic crystal or lattice structure. The most common techniques are based on the optical characteristics of minerals as viewed in a petrographic microscope or their behavior when bombarded by X-rays (e.g., X-ray diffraction), although other procedures may be employed.

17.1.1 Petrographic Characterization

Petrographic analysis is the principal method of identifying minerals in archaeological pottery. The techniques are borrowed from geology, where they are used to study the origin, occurrence, structure, and history of rocks (Artioli 2010: 64–66; Rapp 2002: 19–20). Minerals are identified by their optical properties, that is, their characteristics as observed in a petrographic or polarizing microscope when light is passed through them (as distinct from incident light used to illuminate the surface in ordinary binocular microscopes). Petrographic microscopes include various lenses and filters that modify light transmission in different ways (fig. 17.1). The specific behavior of the light as it is modified by these devices before and after passing through the mineral is the basis for the mineral identification (see Kerr 1977). Minerals may be studied optically through thin sections or grain mounts.

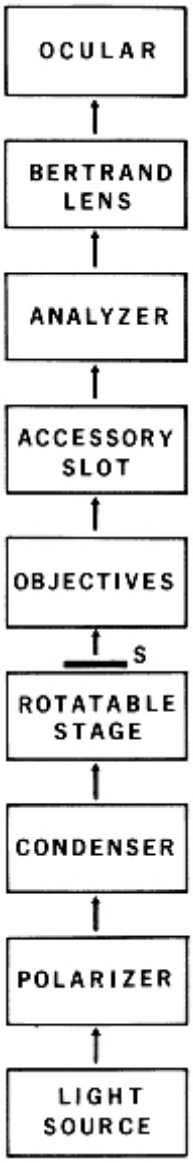

Figure 17.1 Schematic diagram of a petrographic microscope: S = specimen.

Thin sections of ceramic materials are slices taken from a sherd or fired clay briquette, impregnated with an epoxy, mounted on a glass slide, and ground to a uniform thickness of 0.03 mm. They are usually prepared by commercial laboratories. Most thin sections are cross-sections of vessel walls that parallel the vertical axis of the vessel. In coiled vessels these sections sometimes show slight differences in composition or orientation of particles between coils or at their joins. Different orientations of the sections may be useful for other purposes. Horizontal sections (usually parallel to the orifice) or even flat sections parallel to the surfaces may be desirable to study inclusions with elongated or platy shapes (mica, sponge spicules, etc.). These materials often have a preferred orientation as a result of shaping by coiling, thinning, and smoothing. Individual clay platelets are almost always too small to be identified under even high-power objective lenses in petrographic microscopes.

Thin sections allow identification of the kinds of minerals present and their granulometrics: size, sorting, shape, and percentage in the fabric, and the skewness and kurtosis of these distributions (Freestone 1995; Middleton and Freestone 1991; Quinn 2013; Stoltman 1989, 2001). They also permit analysis of mineral associations and orientations, surface treatments (compaction, slips; fig. 17.2), and alterations from firing (cracking) or postdepositional factors such as recrystallization or diagenesis (Stoltman 2001: 323). Porosity can be assessed through examination of the size, shape, and location of voids. The addition of salt to the clay can sometimes be determined in thin sections because the salt reacts with calcareous fragments, leaving a yellow "reaction rim"; cubic voids may not be reliable indicators of salt (Woods 1986: 166–67; cf. Rye 1976).

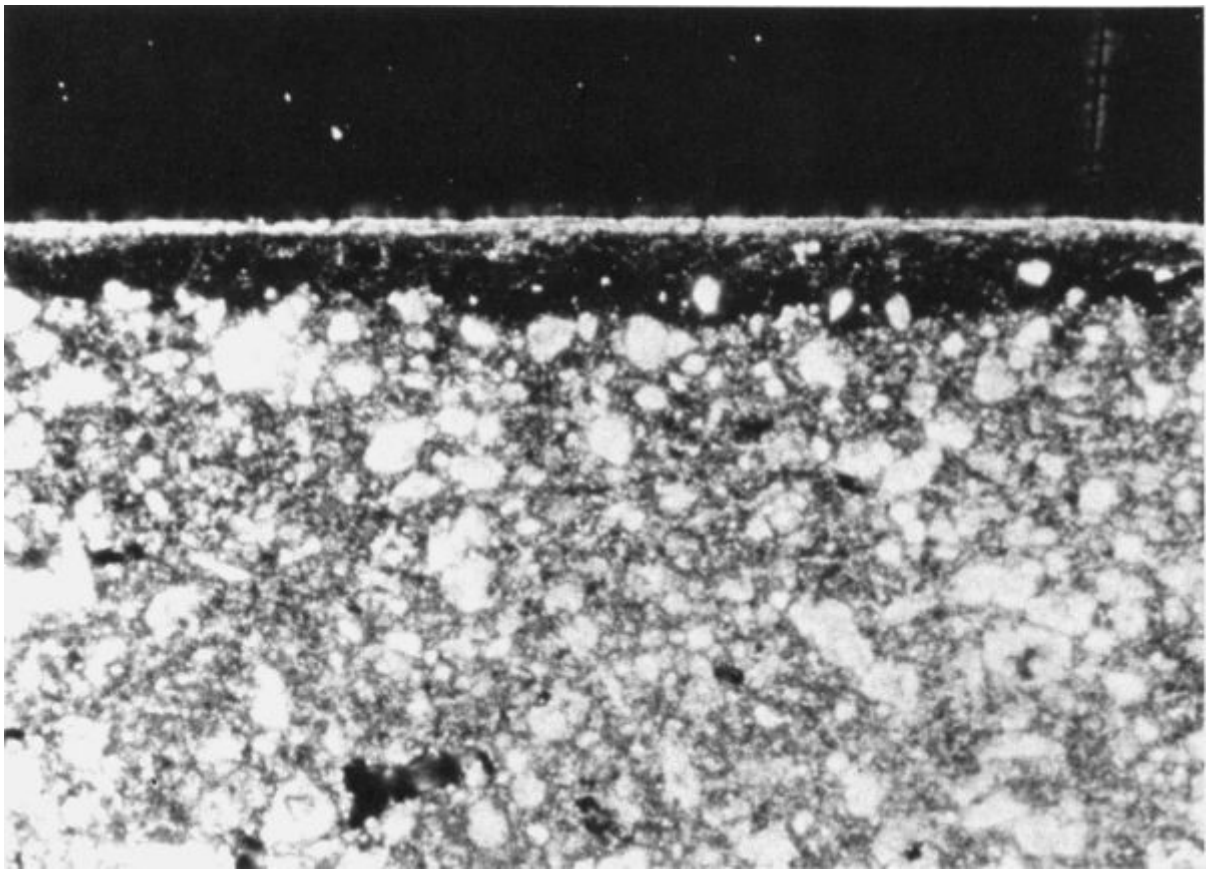

Figure 17.2 Photomicrograph of a thin section of pottery taken at low power (40x) magnification. The vessel has a marly paste, and the bright white particles are calcite. The surface of the sherd shows two layers distinguished by their birefringence (different propagation of light). These represent an opaque white slip covered with a thin, translucent red slip.

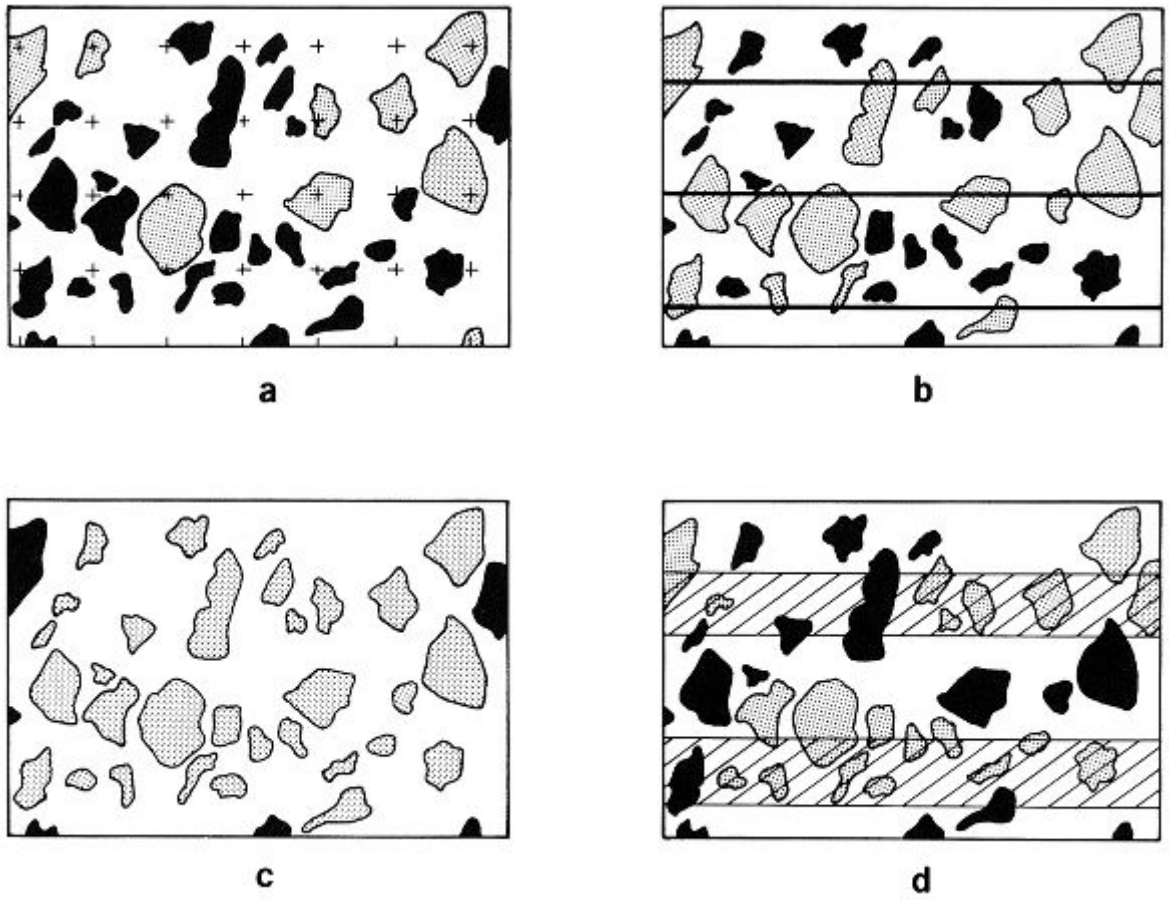

Figure 17.3 Comparison of methods of counting grains in a microscope: Stippling indicates grains that are counted; black grains are not counted: *a*, point count; *b*, line count; *c*, area count; *d*, "ribbon" count. After Middleton et al. 1985: fig. 3.

The percentage of various phases is usually determined by some variant of point counting or modal analysis, whereby grains of different minerals (along with pores and matrix) are counted and measured along traverses over the length of the section using a mechanical stage (fig. 17.3). A range of 100 to 300 grains per thin section is suggested to yield quantitative results with ±3.5% accuracy (Stoltman 2001: 306; see also Stoltman 1989).

Individual minerals from a sherd may be studied as grain mounts. Grains can be recovered by crushing the sherd or by removing the particle from the fabric; separation of clays may be accomplished by sieving or by chemical methods. The grains are then crushed (rather than ground) to about 0.1 mm and the fragments mounted temporarily on glass slides. Grain mounts can also be used to study fragments of glasses and glazes, for example to measure their refractive index (a measure of gloss, which is in turn largely a function of lead content) or birefringence (stress-induced birefringence related to a glaze's fit to the body). Although this approach cannot be used to study associations of minerals and their sizes and shapes, the method is fairly fast and requires little sample preparation if relatively few minerals are of interest.

A common individual-grain study focuses on heavy or accessory minerals (Peacock 1967)—high-density or detrital minerals occurring as tiny, usually highly colored grains in small quantities (less than 1%). A pottery sample of 20–30 g is finely crushed and sieved, the material is separated into light and heavy fractions in a centrifuge (or mixed with a liquid of a high specific gravity), and the heavy minerals are cleaned and mounted on slides for study. Heavy-mineral analysis is especially suitable for the study of coarse sandy (high-quartz) pastes, because sands (whether sedimentary or volcanic) usually contain suites of heavy minerals characteristic of the original parent material (see Blatt 1982: 169).

In general, petrographic methods, particularly thin sectioning, are most appropriate for characterizing a broad range of low-fired pottery. Petrography is relatively inexpensive, so it can be used on a large number of specimens, and certain kinds of useful information can be obtained even with only minimal training. Optical properties allow identification of not only minerals but also their characteristics (e.g., as natural or added), plus other information on the pottery. Moreover, the thin section itself forms a permanent record that can be analyzed repeatedly.

Digital imaging, using scans of a thin section, is a relatively new technique providing a valuable complement or alternative to petrographic analysis (Reedy 2006). Although the latter is more broadly applicable and recommended as a precursor to the former, imaging is particularly helpful, especially if automated, for examination of large numbers of samples and collection of large amounts of supplementary data (Livingood and Cordell 2009). These data have the potential to be informative in combination with quantitative elemental data in multivariate statistical approaches to compositional characterization, including automatic identification of quartz, calcareous material, and pores (Aprile et al. 2014).

17.1.2 X-Ray Diffraction (XRD)

X-ray diffraction analysis is a method of identifying minerals by their crystalline structure through the Bragg equation: $n\lambda = 2d \sin\Theta$ (Artioli 2010: 50–51; for history, see Moore and Reynolds 1997: 5–14). When X-rays are aimed onto a specimen, the atomic planes (d) of its constituent minerals diffract (reflect) the waves along certain directions or angles (Θ) that are picked up by a detector (fig. 17.4). A series of intensities or peaks of the rays at these angles, known as a diffraction pattern, is created (fig. 17.5). The peaks, plus the wavelength (λ) of the rays, allow the mineral to be identified by its characteristic lattice spacings (d). Automated X-ray diffractometers (synchrotron sources are less commonly used) have standard diffraction pattern databanks incorporated into the devices. The method requires approximately 20 mg of powdered sample.

X-ray diffraction of aboriginal pottery—especially low-fired pottery—has to be approached with some caution. The method is only semiquantitative and provides no

information on whether a mineral of interest is naturally present in the clay or added as temper, or on its size, shape, and alteration (Rice 1974). XRD is, however, one of the few mineralogical methods with the potential to identify clay mineral constituents. Clays generally lose their ability to diffract X-rays upon dehydroxylation and loss of crystalline structure on firing (c. 500–600°C). However, pottery fired to temperatures below 800°C or for very short durations (or both) may rehydrate during burial (Kingery 1974; Magetti 1982: 129), regaining the clay's crystalline structure and permitting X-ray identifications.

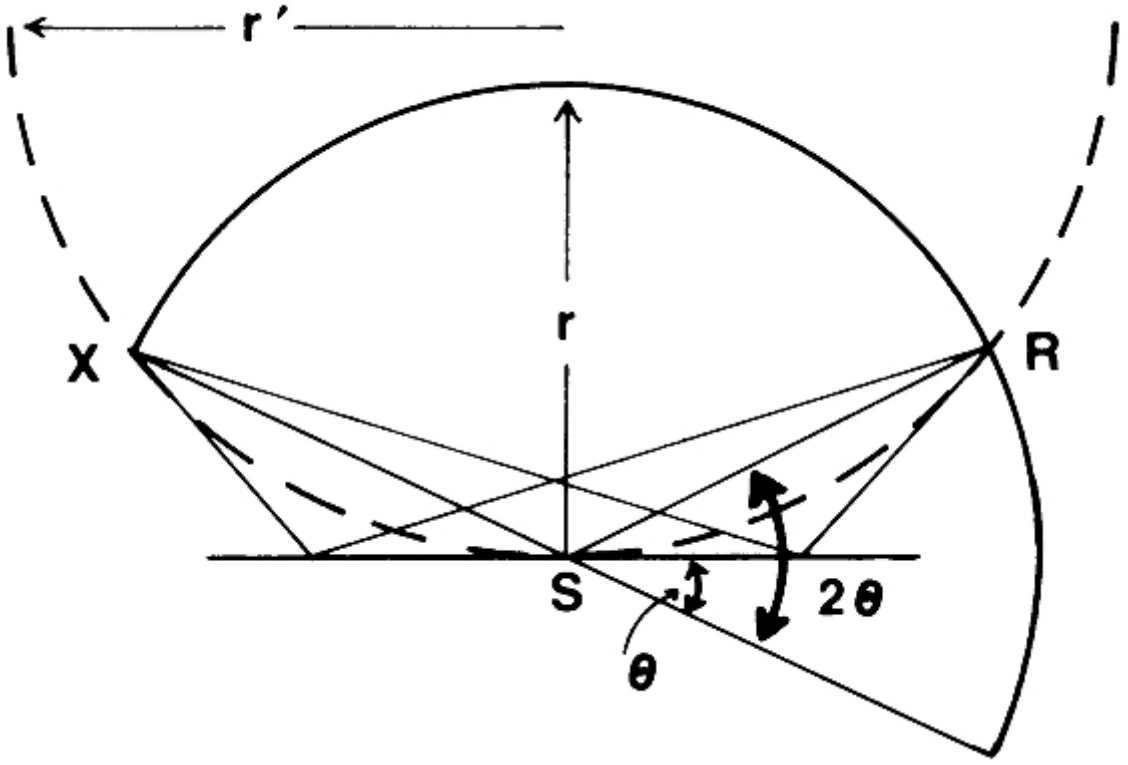

Figure 17.4 Geometry of an X-ray diffractometer: X = source of X-rays; S = specimen; R = receiving slit; r = radius of goniometer; r′ = radius of focusing circle at Bragg angle Θ. After Zussman 1977: fig. 11.

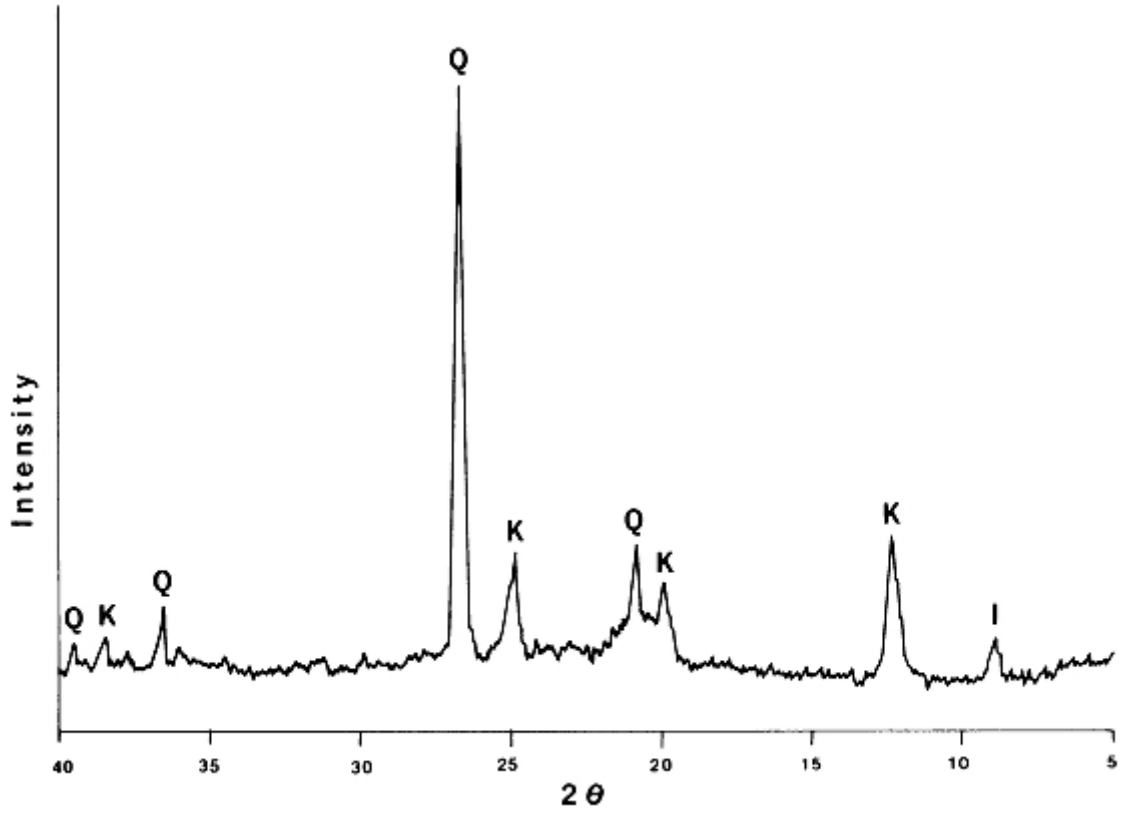

Figure 17.5 X-ray diffraction pattern of an unordered mixture of one-third each of quartz (Q), kaolinite (K), and illite (I). Differences in peak height among the three minerals result from the combined effects of differences in crystal structures and orientation of grains on the glass slide holding the material. Peaks occur when the Bragg equation is satisfied. After Blatt 1982: fig. 3–8.

Nonetheless, XRD may be most useful for identifying high-temperature minerals, such as mullite and tridymite, that form from clays at firing temperatures over approximately 900°C. If the pottery was not originally fired to high temperatures, it can be refired in the laboratory and then analyzed by XRD. Similarly, sample clays can be experimentally fired to high temperatures. In either case it is important to quench the specimen rapidly after firing to avoid the inversion of high-temperature minerals to low-temperature phases.

17.2 Chemical Analysis

Chemical analyses identify the elements (or compounds) in the ceramic, which reside in the mineral components. Elements are typically discussed as major, minor, trace, and ultratrace constituents:

- Major elements, present in amounts of 2% or more, include silica, alumina, oxygen, and frequently also calcium, iron, and potassium. They are usually identified by their oxides, such as SiO_2, Al_2O_3, CaO, and FeO, which are the principal components of the clay mineral fraction as well as many of the clastic minerals in a pottery paste.
- Minor elements are present in amounts between 0.1% and 2% and may include any or all of the following: calcium, iron, potassium, titanium, magnesium, manganese, sodium, chromium, and nickel.
- Trace elements are present in very small quantities of less than 0.1% and are usually measured in parts per million (ppm) or parts per billion (ppb). The term ultratrace is sometimes used for elements in quantities less than 1 ppm. Trace and ultratrace elements include geochemically rare elements such as cesium, rubidium, vanadium, uranium, tantalum, lithium, gold, selenium, antimony, strontium, cobalt, and the fifteen rare earth or lanthanide series elements (atomic numbers 57–71; e.g., lanthanum, cerium, samarium) plus scandium and yttrium.

Because the kinds and amounts of trace elements are uniquely characteristic of individual clays and clay products, they are often referred to as a "fingerprint." Along with the minor elements, trace elements are the basis for most characterizations of pottery composition (Neff 1992b).

Many modern methods of chemical analysis are spectroscopic or spectrometric techniques, so called because they are based on the electromagnetic spectrum of radiant energy (see fig. 16.1). That is, when energy is introduced into a sample—for example, by heating or by bombardment with X-rays, electrons, or neutrons— the atoms in the constituent elements respond in known ways. They either emit detectable levels of resultant energy (in the form of visible light or X-rays, gamma-rays, etc.) or they absorb some of the introduced energy. Most of the methods used in analyzing pottery are variants of emission spectrometry, meaning that they measure the wavelength of the energy emitted by the sample to determine the kind and quantity of elements present. The output of the various analyses consists of spectra giving the precise wavelengths of the emitted or absorbed radiation by the unknowns in the specimen (see Artioli 2010: chap. 2). These wavelengths are characteristic of the properties of the constituent elements through their crystal lattice structure (atoms and electrons). Identifications are automated through databases of known spectra programed into the instrumentation.

Because the chemistry of a ceramic fabric is directly related to its mineralogy, chemical analysis generally measures the elements or compounds as bulk composition —that is, the whole object as clay-plus-temper, rather than a specific mineral fraction. The same element may occur as an oxide or a compound in several minerals in a single pottery fabric, and the bulk chemical composition is a sum of all those occurrences. Thus there is usually no attempt at achieving a one-to-one correspondence between the

presence or amount of one particular element, oxide, or compound and the occurrence of a single mineral in the mixture. Similarly, bulk analyses provide no information on how a particular element became a part of the ceramic—whether it is a constituent of the clay or originated in an added inclusion. This is more easily determined from thin sections.

Commonly used spectrometric techniques for chemical compositional characterization include neutron activation analysis, LA-ICP-MS, X-ray fluorescence, and PIXE. These, however, represent only a portion of the techniques available for analyzing pottery and artifacts in general (for discussion of methods and case studies, see, e.g., Artioli 2010; Goffer 2007; Pollard 2007; Pollard et al. 2008; Price and Burton 2010). Various point-analysis methods permit the composition of slips, paints, postfire-applied substances, and glazes to be analyzed separately from the clay body. In the same way, a tiny area (such as an inclusion) of the ceramic body may be analyzed in microprobe fashion.

17.2.1 Instrumental Neutron Activation Analysis (INAA)

Neutron activation analysis, first used in the 1930s and applied to archaeological artifacts in the late 1950s (Emeleus 1960; Sayre and Dodson 1957; Sayre et al. 1958), quickly became a significant technique in ceramic compositional studies. The method requires a source of thermal (low-energy, or slow) neutrons, usually a nuclear reactor with research functions or, more recently, a particle accelerator (a synchrotron). This restricts the locations where INAA can be carried out and most artifact studies are performed at only a small number of major research facilities scattered over the world (in the United States, the Missouri University Research Reactor [MURR], Glascock 1992; the Oregon State University Radiation center, http://people.oregonstate.edu/~mincl/Archaeometry_index.htm; the Smithsonian-NIST program; Blackman and Bishop 2007).

In INAA, a powdered sample of the pottery is bombarded with neutrons. This changes the elements into unstable radioactive isotopes, which decay at known rates (half-lives) to stable isotopes. The gamma rays emitted during decay are analyzed several times after increasing periods to identify elements with different half-lives. By determining the energy levels of the emitted gamma rays, the individual elements in the sample can be identified; by calculating their intensities (the number of gamma photons), their concentrations can be estimated. The analytical results are typically presented in terms of groupings of samples having similar elemental compositions that are created by complex multivariate statistical transformations (fig. 17.6; Baxter 1992, 2006; Bishop et al. 1982: 305; Neff 1988, 1989, 1992b, 1993).

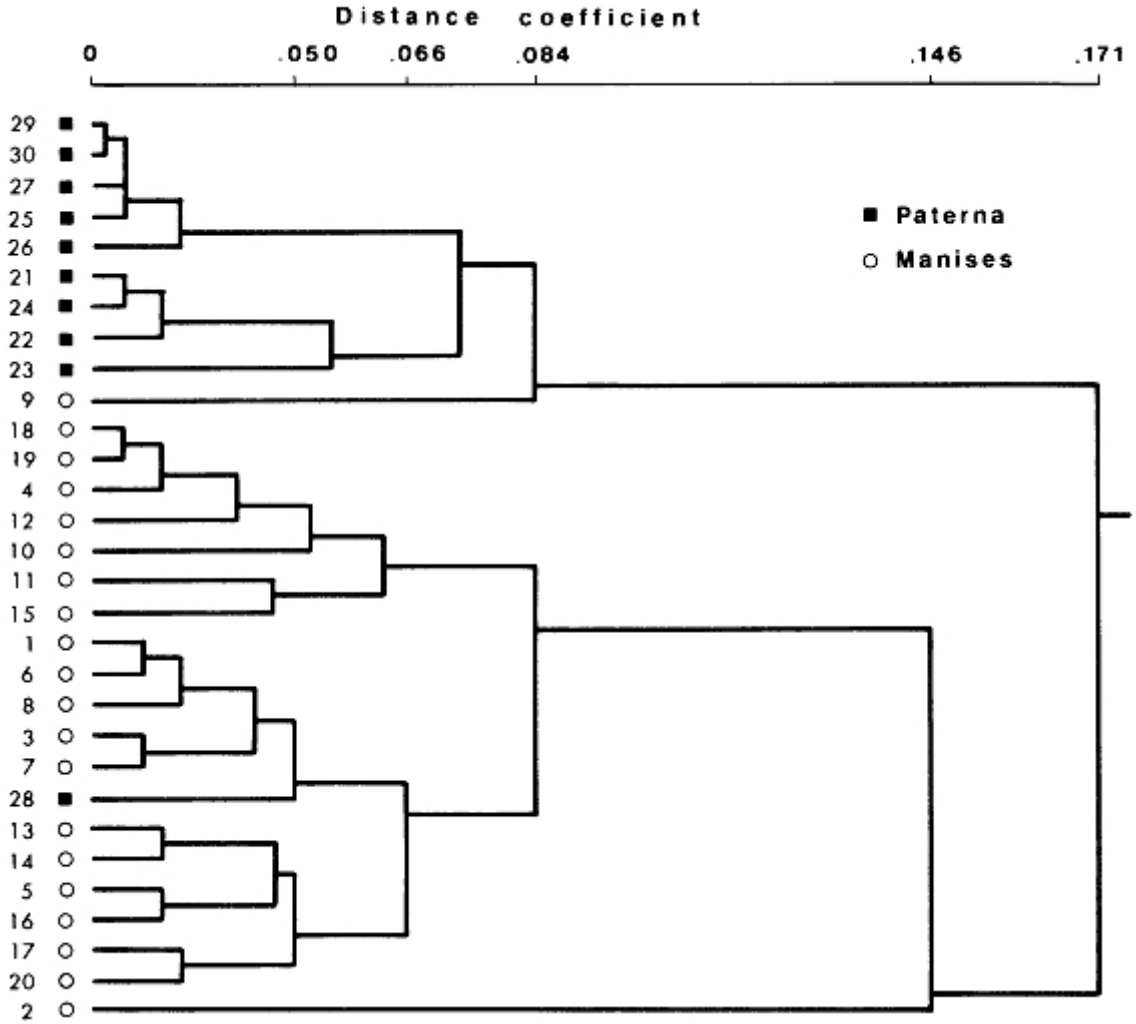

Figure 17.6 Dendrogram depicting results of hierarchical agglomerative cluster analysis of minor and trace element concentrations in samples of pottery from two sites, Paterna and Manises, Spain. The two compositional groups are clearly separated. After Jornet et al. 1985: fig. 9.

Several things can be done inferentially with these groupings depending on the goals of the study. For example, the analysis may have been undertaken for simple characterization alone, to understand the composition of the pottery most commonly found at a site (fig. 17.7). In such cases, the groupings created through the compositional data can be intercompared or compared with the results of typological classification. Or, the groups may be the basis for pottery provenience/provenance determinations (chap. 20).

INAA has many advantages for compositional analysis of pottery. The technique is extremely sensitive, able to detect about 75 of the 92 naturally occurring elements (Bishop et al. 1982: 292) in minor, trace, and ultratrace amounts. Sample size is very small, preparation time is low, and the method has been completely automated. INAA is extremely sensitive to concentrations as low as parts per billion, and the accuracy of quantitative determinations can usually be given within ±5%, or sometimes ±1%.

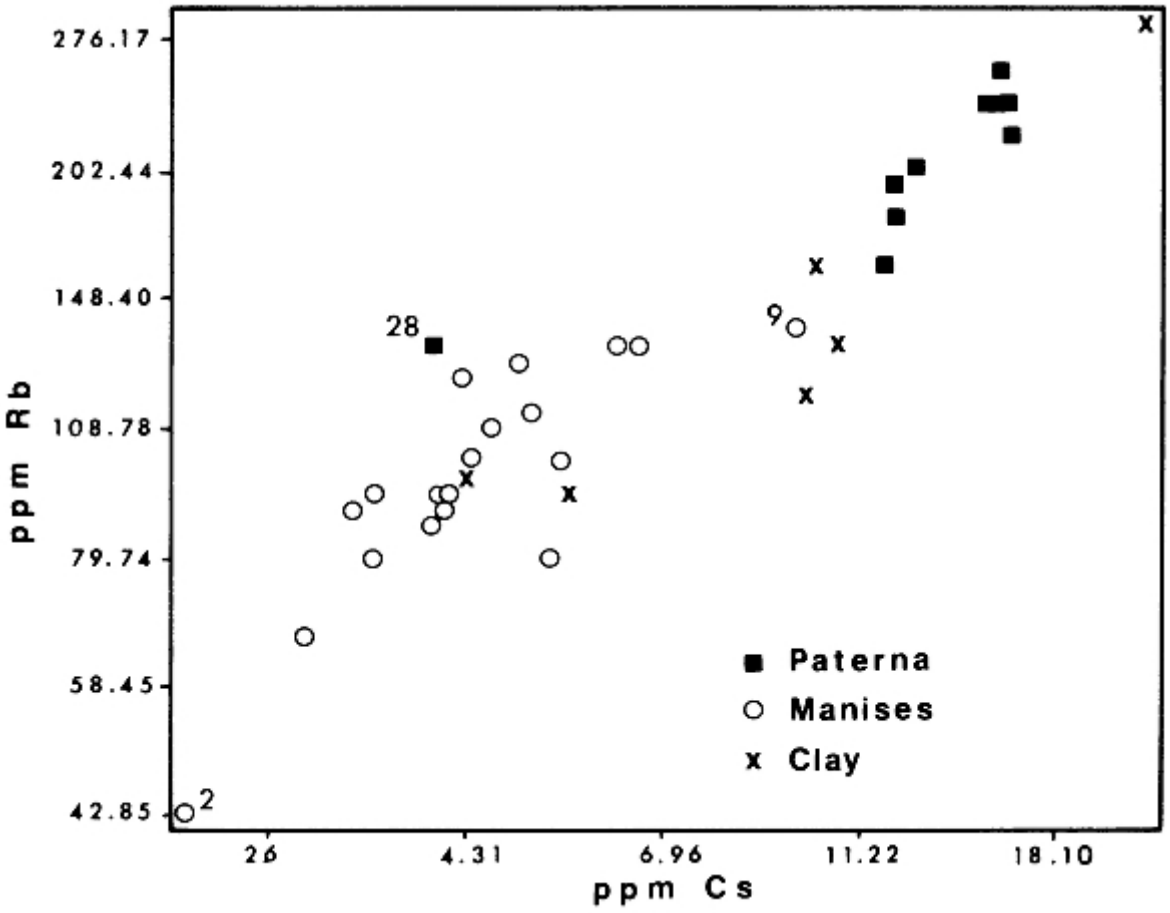

Figure 17.7 Scatter diagram showing separation of Paterna and Manises pottery samples (plus clay samples) on the basis of concentrations of Rb versus Cs. After Jornet et al. 1985: fig. 10.

17.2.2 Laser Ablation–Inductively Coupled Plasma–Mass Spectrometry (LA-ICP-MS)

In mass spectrometry (MS), the atoms of elements in a sample are converted into ions (usually cations) by any of several methods. These ions are separated by their atomic mass (weight) and electrical charge in a high-vacuum analyzer, and then the mass-to-charge ratios are measured to determine the elements present. In "inductively coupled plasma" (ICP) MS, argon plasma (gas) is used as the ionizing source. ICP-MS is useful for quantitative analysis of trace and ultratrace elements, and is capable of analyzing more elements and elements present in smaller amounts than can INAA (see Stoner and Glascock 2012). It may eventually replace INAA as the preferred technique for provenience analyses.

Laser ablation (LA) is a technique that uses a laser beam to remove (ablate) a thin layer from the surface of the sample, the removed particles being analyzed by the ICP-MS system (Gratuze et al. 2001). For pottery, especially heterogeneous pottery, LA-ICP-MS is best used as a technique for point analysis or analysis of surface materials (glazes, slips, pigments) (see Speakman and Neff 2005; cf. Stoner and Glascock 2012).

The technique is flexible and easily optimized to address the particular problem at hand. One difficulty, however, is the need to use known internal standards in the analyses (Gratuze et al. 2001; Wallis and Kamenov 2013).

Other variants of the ICP-MS technique for pottery pigment analysis include microwave digestion of the sample (Kennett et al. 2002) and time of flight LA-ICP-MS (Duwe and Neff 2007; Golitko et al. 2012).

17.2.3 X-Ray Fluorescence Spectroscopy (XRF)

In X-ray fluorescence analysis (Artioli 2010: 34–37; Beckhoff et al. 2006; Jenkins 1999; Mantler and Schreiner 2000), a specimen is irradiated with primary X-rays from an X-ray tube or from radioactive sources. These X-rays displace electrons from the inner orbits of the constituent atoms, which are then filled by electrons from the outer levels. The energy released in this process is emitted as secondary or fluorescent X-rays, the wavelengths of which are unique to each element and form the basis for the identifications.

XRF analysis can be used to investigate about 80 elements present in major, minor, and trace quantities, and is best with those above atomic number 12 (magnesium) on the periodic chart. Numerous variants of XRF are available for specialized analyses, including energy-dispersive (EDXRF) and wavelength-dispersive (WDXRF) spectrometer detection system set-ups for point analyses. In addition, portable XRF (pXRF) spectrometers are now available (Frahm 2013; Frahm and Doonan 2013; Shackley 2010; Speakman and Shackley 2013).

Samples for XRF can be prepared in several ways. If the artifact is small the entire object can be inserted into the apparatus rather than removing a sample, thus making the method completely nondestructive. The method analyzes only the surface of the artifact, making it effective for characterizing pottery surface coatings such as glazes, slips, or paints. Otherwise a small sample (from 100 mg up to 2 g) of the pottery must be removed, powdered, and formed into a pellet.

X-ray fluorescence spectrometry is widely available and relatively low in cost, and may be nondestructive for very small artifacts. The technique has relatively high precision (usually better than ±5%) and for large numbers of samples it can be fully automated. The principal disadvantage of X-ray fluorescence analysis is that quantitative measurements are extremely sensitive to the thickness and shape ("geometry") of the specimen. Comparisons of sherd compositions analyzed by both INAA and pXRF suggested that the greater precision of INAA makes this method preferable for ceramic provenience analyses (Speakman et al. 2011).

17.2.4 Proton-Induced X-Ray Emission Spectroscopy (PIXE)

Proton (or particle)-induced X-ray emission analysis, or PIXE (Artioli 2010: 313–17; Dran et al. 2000; Johansson et al. 1995), is a technique in which a beam of protons

interacts with atoms in the sample. As in XRF, an electron is removed from the inner orbit, a higher-orbit electron moves into the vacancy, and an X-ray is emitted. The element is identified on the basis of the energy (wavelength) of the X-rays. This multi-element method cannot be used for elements heavier than sodium (atomic number 11) and is sensitive to the ppm level.

For ceramics, PIXE is particularly suited to the analysis of the composition of surface materials, such as slips, paints, and glazes, and the beam can be focused for point analysis. The technique can be nondestructive and an entire vessel may be submitted to the external-beam technique, rather than as a sample introduced into the apparatus. For bulk composition of the body of a ceramic, a very small sample must be pelletized.

18 Physical and Mechanical Properties

> To make stout, water-tight pottery out of clay which is friable and unstable, liable to pulverize or crack (which, however, is possible only if from a large number of organic and inorganic materials, the one most suitable for refining it is selected, and also the appropriate fuel, the temperature and duration of firing and the effective degree of oxidation) . . . required a genuinely scientific attitude, sustained and watchful interest and a desire for knowledge for its own sake.
>
> Lévi-Strauss 1966: 14

The success of pottery manufacture as a livelihood ultimately rests on the durability and serviceability of the products in reliably fulfilling their intended uses, including containing liquids, withstanding accidental impacts, and surviving repeated heating and cooling cycles. Success in use, in turn, is a function of key physical, mechanical, and thermal properties, which can be assessed by various techniques, ranging from simple to complex.

Two cautions should be observed in interpreting these features in archaeological pottery. First, although there may be a correlation between certain properties of the ceramic and the requirements of specific uses, for example, between thermal expansion coefficients and cooking, this does not necessarily mean that relationship was consciously invoked as the vessel was manufactured. Second, because of the varied processes relating to the pot's usage and to the postdepositional conditions over the centuries or millennia since its discard, the measured properties of an excavated sherd may differ from those of the new vessel. What are measured are a sherd's current physical, mechanical, and thermal properties—generally referred to as remnant or residual properties—given that its initial characteristics might have been modified by use and postdepositional processes. The findings of characterization analyses represent an estimate or approximation of those original characteristics, but are not necessarily equivalent to them.

18.1 Properties, Microstructure, and Stresses

A fired ceramic, whether ancient or modern, art object or industrial good, can be characterized as a relatively hard, brittle, stable material with a very high melting point, high compressive strength, and good thermal conductivity. This statement describes some of pottery's "performance characteristics"—that is, traits relating to how an object performs in use. Understanding performance is a frequent research focus of ethnoarchaeologists and selectionist and behavioralist archaeologists (see O'Brien et al. 1994; Skibo 2013: chap. 2).

The physical properties of a ceramic refer to its appearance and functional capabilities. Many visual characteristics of a ceramic that provide evidence of composition and manufacture—surface or internal imperfections, texture, dark coring, surface treatment and color, shape and size—directly relate to how the object performs in use. Along with firing shrinkage and estimated firing temperature, they influence properties such as portability, porosity, permeability, hardness, and strength.

Mechanical properties of ceramics are also performance-related and tend to be conceptualized in terms of resistance to various stress forces, such as compression, impact, or abrasion. These properties are often identified as "intrinsic" and characterize the physical and mechanical behavior of a ceramic. Intrinsic properties discussed here include modulus of elasticity, Poisson's ratio, and strength, typically expressed as the modulus of rupture. Two others, thermal conductivity and the thermal expansion coefficient, relate to pottery's behavior with heating and cooling (chap.19).

18.1.1 Microstructure

Physical and mechanical properties are closely related to the internal structure of a ceramic. This structure has two aspects: the arrangement of atoms within its components (see chap. 2) and the arrangements of these components with respect to each other. With respect to the former, pottery can be described in engineering terms as a material consisting of more than one "phase." A phase (fig. 18.1) is "any part of a system which is physically homogeneous and bounded by a surface, and that is mechanically separable from other parts of the system" under specified conditions of pressure, temperature, and composition (Kingery 1960: 248). Phases in ceramics include individual grains, glassy material, and pores.

The complex arrangement of phases is referred to as the ceramic's microstructure: the internal arrangement of crystalline and amorphous (glassy) materials, voids (pores), and the boundaries between them in a polycrystalline and (usually) polyphasic medium. Microstructure is generally discussed in terms of four properties: composition, texture, structure, and surface characteristics (Wolkodoff et al. 1968: 297).

- Composition refers to the identity of the crystalline and noncrystalline (glassy) phases and the pores.
- Texture is a function of the size, shape, and orientation of individual phases.

· Structure refers to the physical arrangement of the phases.
· Surface characteristics include all these features as they are visible under a microscope on ground, polished, and fractured surfaces in sections or replicas.

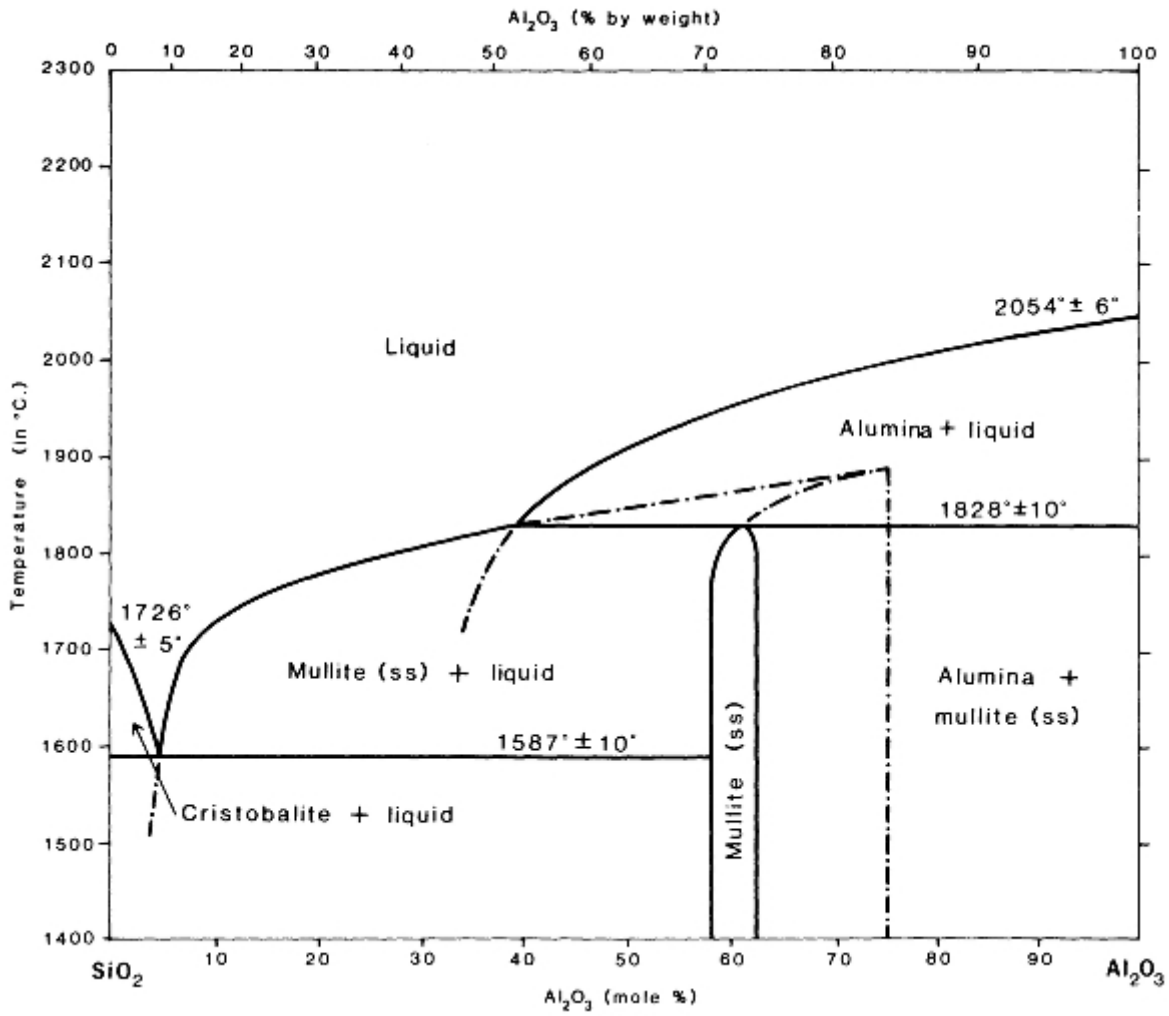

Figure 18.1 A phase equilibrium diagram for the system $Al_2O_3 \cdot SiO_2$, showing changes in liquid and solid components as a function of temperature. Solid line indicates stable equilibrium; broken line indicates metastable extension of liquidus and solidus lines for mullite; ss = solid solution. After Kingery et al. 1976: fig. 7.28.

Phase relations among constituents are significant with respect to the durability of low-fired, heterogeneous archaeological pottery. The boundaries or contact planes between phases can be a source of weakness, and the crystals themselves have cleavages and fracture planes that will vary in strength at different temperatures. In addition, the strength of multiphase ceramics decreases significantly with increasing grain size (Chu 1968: 853; see also Kirchner 1979: 8). Generally, smaller grain size contributes to greater bending strength and higher resistance to crack initiation.

These microstructural relations are especially important in the case of preexisting boundary stresses between mineral phases with different thermal expansion coefficients. They may be especially significant at high temperatures with respect to

quartz inclusions (Robinson 1968b: 550–51; Warshaw and Seider 1968), because of the inversions quartz undergoes at high temperatures and again on cooling. These quartz problems are minimal in low-fired archaeological pottery, in part because only the low-temperature alpha-beta inversion is likely to take place and it occurs on heating, while there is still considerable porosity in the vessel to absorb the stresses.

The microstructural characteristics of a ceramic underlie virtually all its use-related physical and mechanical properties: for traditional pottery vessels the most important are porosity, hardness, and strength. In low-fired, polycrystalline pottery such as terracottas and earthenwares, the primary determinants of microstructure are the raw materials, fabricating techniques (including firing), and possible phase changes in sintering. In high-fired ceramics such as porcelains, the equilibrium relations among phases and the changes resulting from vitrification and high-temperature mineral formation are more important. The special character and performance of ceramic objects as containers—their ability to hold liquids and to withstand sharp temperature changes—are conferred by features of microstructure.

18.1.2 Physical and Mechanical Stresses

The properties of a ceramic that affect its use and use-life need to be understood in terms of the various sources of physical, mechanical, and thermal stresses and strains it will experience.

- Stress may be defined as applied force (or load) per unit area.
- Strain is the response to stress forces: the change in dimension per unit dimension in a material deformed by stress.

At low stresses the strains in most solids are proportional to the stresses and are reversible; the material is said to exhibit "elastic" behavior. In materials science, the term elastic refers to the ability of a solid (a crystal or ceramic) to return to its original state after being deformed by an external force. This is known as elastic or temporary deformation; it is reversible. Too much stress will exceed the material's elastic limit, which is the maximum stress that can be withstood without permanent distortion. The result is "plastic" deformation and irreversible changes in structure. Ceramics have low elasticity, which is another way of saying that they are brittle.

The role of these stresses and strains in pottery can be understood by comparing ceramics with metals. Metals are malleable and ductile; they absorb and accommodate stress forces through plastic (permanent) deformation, distorting their shape to some degree before rupturing. Ceramics react differently. Although wet clays are highly plastic and can distort without failure in response to varied forces (see sec. 3.2.2)—this is what allows them to be shaped in varying ways—fired ceramic materials are rigid: they experience "brittle fracture" and breakage without plastic deformation. This response is partly a consequence of the types of atomic bonding in ceramic materials: their mixed covalent/ionic bonds are rigid and strongly directional and allow little or

no plastic flow, in contrast to the responses of materials with metallic bonding (Grimshaw 1971: 836, 837).

The linear relations of stress and strain are given by two intrinsic properties of a ceramic: the modulus of elasticity (e.g., Young's modulus, *E*) and Poisson's ratio (Shackelford 2005: 190–92; see also Kilikoglou and Vekinis 2002):

- Moduli of elasticity, *E*, are measures of a ceramic's stiffness: its ability to resist mechanical stresses (tensile, shear) without deformation or failure. It is measured as the ratio of stress to strain derived from the change in dimension of the specimen under applied force (Grimshaw 1971: 864).
- Poisson's ratio (**ν**) is a measure of elastic response: the relation between strains occurring in perpendicular directions (shear). For example, as a piece is being "stretched," the longitudinal strain of elongation is accompanied by transverse strains in a direction perpendicular to the elongation. Poisson's ratio is thus a ratio of lateral to longitudinal strains (Grimshaw 1971: 839).

Six kinds of physical or mechanical stresses have been analyzed by materials scientists on high-fired ceramics (fig. 18.2): tensile, shear, compressive, transverse, torsional, and impact stresses (Grimshaw 1971: 832–34, 842–55):

- Tensile stress (fig. 18.2*b*) results when tension or extension forces are applied to a material, tending to pull it apart across a plane at right angles to the direction of the force. Tensile stresses are especially significant during cooling (see Kingery 1955: 12), and tensile strength is an extremely important property of ceramic glazes, as it prevents them from crazing on cooling (sec. 7.3). As noted, ceramic materials are brittle, with low elasticity, which means that they have low tensile strength (see Beck 2002; Neupert 1994).
- Shear stresses (fig. 18.2*c*) occur when one part of the body is made to slip or slide relative to another part. Shear results from two non-colinear stresses applied in opposite directions, and tensile forces develop at an angle of approximately 45° to the shearing force, leading to fracturing. The relation between stress and strain during shearing is summarized by a constant known as the modulus of rigidity, E_R (Grimshaw 1971: 839). Wet unfired clays have low resistance to shear; the shear strain that develops is part of their plasticity and their failure (cracking) ultimately occurs because their limit of strain is exceeded.
- Compressive stress (fig. 18.2*a*) occurs with application of a crushing force, as in load-bearing structures such as a brick wall. Also, glazes may compress the body as they shrink in cooling, strengthening the ware up to a certain point beyond which the glaze will craze or crawl (see figs. 7.1, 7.2). Compressive stress/strain relationships, as in the case of tensile stresses, are expressed by *E*. Fracture lines usually follow the flaws and cracks inherent in the material, with large grains acting as barriers. The compressive strength of ceramics has been estimated at roughly four times its tensile strength (Kingery 1955: 12).
- Transverse or flexural stress (fig. 18.2*e*) is an applied force that causes bending. The bending strength of a ceramic is approximately twice the tensile strength (Davidge and Tappin 1967: 417).
- Torsional stresses (fig. 18.2*d*) are twisting or rotational forces applied to a material and may occur when different parts of a material are subjected to forces in different directions. The strain is basically one of shear and is marked by a characteristic S-shaped fracture.
- Impact stresses (fig. 18.2*f*) occur when force is applied suddenly and with momentum, as in a sharp blow. The stress is generally one that if applied slowly would not cause failure, but because brittle bodies such as ceramics cannot transmit the energy fast enough to disperse it throughout the body, local strains can be very large, causing the piece to fail/break. The direction of the stress is determined by the direction of momentum of the impact, and the initial fracture is caused by tensile stress (Grimshaw 1971: 843).

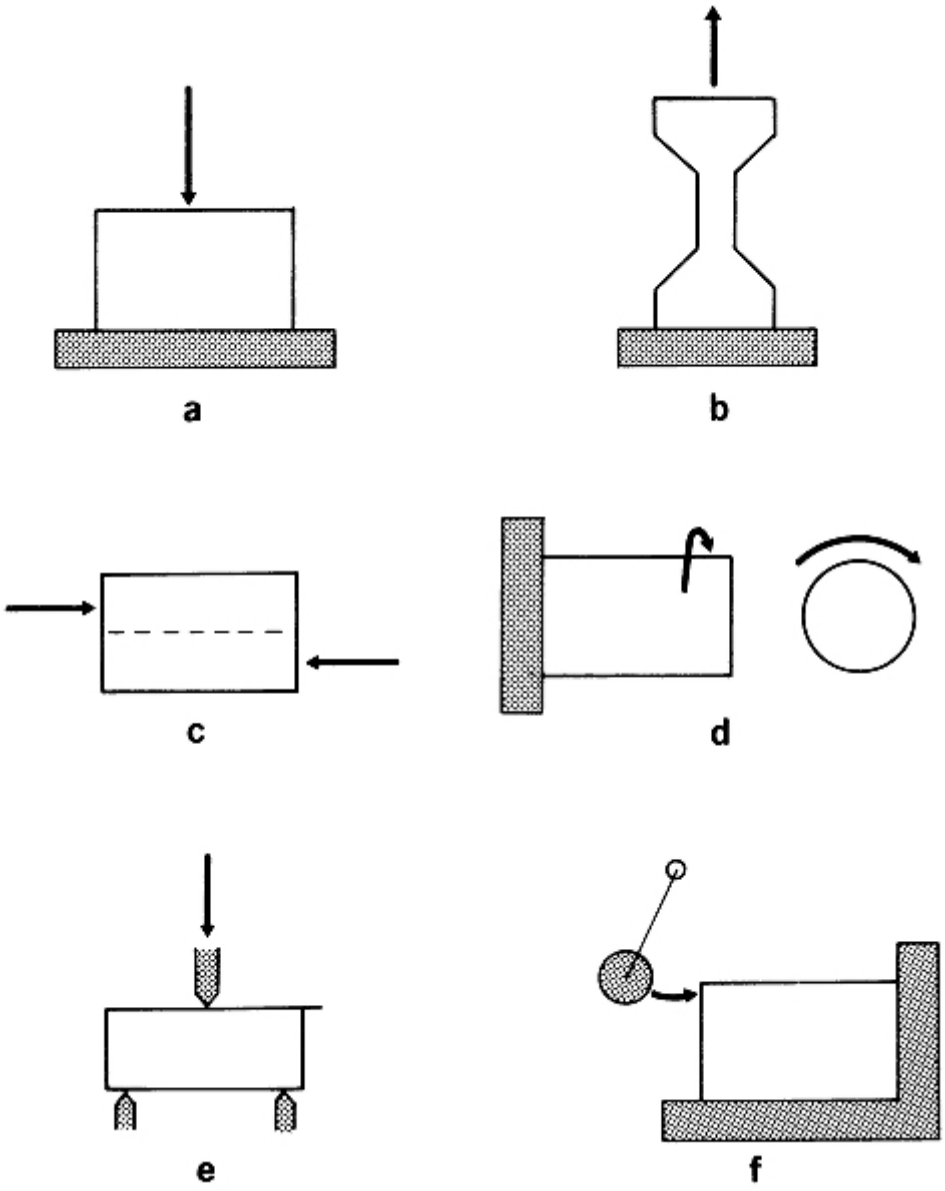

Figure 18.2 The principal methods of applying stress: *a*, compression; *b*, tension; *c*, shear; *d*, torsion; *e*, transverse; *f*, impact. After Grimshaw 1971: fig. XIII.1.

In general it is impossible to apply one type of stress without others; for example, while tensile forces act on a material in one direction, compressive strains are developing at right angles to the direction of force. In ceramic materials, virtually all failure results from either tensile or shear stresses, regardless of how the forces are applied. Moreover, most of these stresses play a significant role not only in mechanical performance, but also in thermal behavior.

18.2 Hardness and Strength

A vessel's durability and ability to withstand mechanical stresses during normal use depends largely on its hardness and strength. These closely related properties refer to the ability of a ceramic to tolerate or resist stresses such as penetration (its stiffness), impact shattering or failure impact (its integrity, elasticity), or deformation (e.g., by compression).

- Hardness is a measure of the response of a ceramic to stresses affecting the surface.
- Strength refers to resistance to stresses involving the entire ceramic body.

Hardness and strength are important to vessel viability in both the unfired (green) and fired states, and are closely related to composition and microstructure: the kind, size, shape, and proportions of the clay and inclusion phases in a ceramic. Firing can be manipulated to modify this relationship because, in general, vessels that are fired to higher temperatures will be harder. Thus better-fired vessels are more resistant to mechanical stress, but strength and hardness also relate to other characteristics.

18.2.1 Hardness

The hardness of a ceramic can mean many things, including resistance to penetration, abrasion, scratching, and crushing (Shepard 1976: 113). Hardness is also related to the stiffness (coefficient of elasticity) of a material. The hardness of a fired clay depends on multiple variables, the most important being firing conditions, impurities, microstructure, and surface treatment.

- Hardness generally increases with the time and especially the temperature of firing, ceteris paribus, but it is also affected by the atmosphere: an atmosphere of reduction (or even severely limited oxidation) for some interval during the firing increases hardness. This occurs because under reducing conditions iron compounds begin to act as a flux, bringing about sintering at a lower temperature than usual.
- Other impurities in the clay besides iron, such as compounds of alkali metals, including sodium and potassium, may act as fluxes, lowering the temperature at which sintering begins and increasing the fired hardness. Sintering and subsequent vitrification result in a hard, glassy body that resists surface deformation. Still other impurities, such as salts, may lower surface hardness if they concentrate on the surfaces of the piece as a soft, scummy residue.
- Microstructural features influencing hardness include grain size and the porosity of the fired piece. Finer-grained, relatively nonporous materials will provide greater resistance to penetration, abrasion, and crushing and thus be generally harder and more durable than coarse, porous materials.
- Surface treatment of a clay piece can also affect its hardness. Burnishing, for example, will compact and smooth the particles on the surfaces, making them harder and more resistant to abrasion. Similarly, a coating of a different material, such as a slip or glaze, may be harder, more resilient, and more resistant to abrasion than the clay body.

Hardness is typically interpreted in terms of firing technology, with greater hardness interpreted as indicating higher firing temperatures. Although this relation generally holds, inferences of firing technology from hardness measurements are reliable only

within the comparative context of a known series of related clays or sherds of identical composition. In other words, differences in hardness between red paste pottery and white paste pottery cannot be confidently attributed to differences in firing temperatures unless the effect of firing temperature on local red- and white-firing clays has previously been determined by independent experimentation (e.g., firing and refiring tests). This is among the many reasons to conduct firing experiments with local clays: to test this relationship. As Anna Shepard (1976: 114) observed, "if identity of paste can be established for a series of sherds, then variations in hardness will reflect differences in firing conditions, but uniformity of hardness does not prove identical firing temperature when pots differ in composition."

18.2.2 Strength

Strength is perhaps the most complex of the use-related properties and in some ways may be considered a composite of them all: composition; method of forming; conditions of drying and firing; physical, mechanical, and thermal properties; resistance to stresses; and conditions of use and other conditions to which it may have been subjected (Grimshaw 1971: 871). Strength refers to the integrity or durability or toughness of a ceramic body (not just its surfaces)—its resistance to breakage and its ability to perform whatever service is demanded of it without cracking, crumbling, warping, shattering, deforming, or otherwise failing (Grimshaw 1971: 832). A strong vessel should be able to survive contact with hot fires or cold liquids, accidental blows, and other conditions of normal use-related wear and tear.

Box 18.1 Measuring Hardness

The hardness of archaeological pottery has long been informally assessed in the field by various impressionistic but nonetheless useful observations, such as a "clinky" sound when a sherd is tapped, or by the way it breaks. These informal assessments are too imprecise to provide any quantitative measure of hardness, however, and for such determinations several laboratory methods exist (Grimshaw 1971: 866–70; Shepard 1976: 15, 114–16). These measure three dimensions of surface hardness: resistance to penetration, resistance to abrasion, and "scratch hardness," which is in some senses a combination of the other two.

Penetration or indentation methods of measuring hardness include the Brinnell, Knoop, and Vickers techniques. These tests are all similar in that a static load is gradually applied to a polished specimen; hardness is calculated by dividing the applied load (force) by the area of the surface indentation on the specimen as measured under a microscope. The primary difference between them is that the Knoop and Vickers tests use a pyramidal diamond point, which leaves a square indentation, whereas the Brinnell test uses a steel ball, which leaves a circular indentation. The similar ball-on-three-ball test has been used satisfactorily on archaeological specimens (Beck 2002; Neupert 1994).

Abrasion or abradability hardness tests measure debris removed from a specimen that has been either tumbled, ground, or blasted with a harder material.

Perhaps the most familiar hardness testing procedure used by archaeologists is the Mohs' mineral hardness scale, devised by an Austrian mineralogist, Friedrich Mohs, in 1822. This scale uses a sequence of minerals of increasing hardness, ranked from 1 to 10 (see table 18.1), talc being the softest and diamond the hardest. Mohs' test measures scratch hardness, or the ease with which the minerals will produce an indentation or scratch when drawn over the surface of a specimen. A Mohs Hardness kit is available for purchase from scientific supply companies.

Table 18.1 Mohs' Hardness Scale and Substitutes

Hardness Number	Mohs' Mineral	Substitute
1	Talc	
2	Gypsum (selenite)	
2.5		Fingernail
3	Calcite	Copper wire
3.5		Celestite
4	Fluorite	
4.5		Window glass; chabazite
5	Apatite	
5.5		Blade of pocketknife; willemite
6	Orthoclase	
6.5		File; vesuvianite
7	Quartz	
8	Topaz	
9	Sapphire; corundum	
10	Diamond	

Source: Substitutes after Grimshaw 1971: table XIII-III; March 1934: 20.

Mohs' test is performed under a binocular microscope, beginning with minerals at the harder end of the scale and moving toward softer minerals. The hardness value of the test specimen is recorded as the hardness of the mineral that will just produce a visible scratch; if the ceramic is harder than the test mineral, the apparent "streak" visible on the specimen's surface comes from the abraded test mineral. Hardness values frequently are interpolated between two minerals, so that a given specimen may be judged to have a hardness of 4.5 if apatite, with a hardness of 5, scratches its surface but fluorite, hardness 4, does not. Non–kiln-fired pottery commonly ranges between 3 and 5 in hardness, but values of 2 and 7 are not unknown.

Mohs' Hardness scale has a number of advantages for archaeologists. One advantage is that it can be readily interpreted in terms reflecting the actual use and serviceability of a pot. The testing procedure is analogous to stirring or scraping, which abrades the interiors of vessels and the surfaces of serving pieces (see Norton 1970: 199). Few actual uses of pots lead to indentation or penetration. The kit of minerals is readily available from scientific supply companies and is easy to use with minimal equipment. In addition, there are several convenient substitutes or approximations for particular values in the scale: a fingernail, for example, averages 2 or 2.5, copper wire is 3, window glass is 4.5, and a pocketknife is about 6 (see also Peacock 1977: 30).

Nevertheless, some cautions should be heeded in applying the Mohs' mineral scale to archaeological specimens. First, the same person should do all measurements, because the pressure applied in drawing the minerals over the specimens will vary from individual to individual. Second, the test is not likely to be reliable on extremely rough ("sandy") ceramics. Third, both surfaces of a sherd should be measured, and it should be clearly noted whether the hardness value is that of the clay body or an overlying slip or glaze.

In addition, several problems are inherent in the scale itself. One is that the minerals in the kits usually vary in the sharpness of their points, and hence in their propensity to cut. Second, the mineral set represents an ordinal rather than a ratio or interval scale—the differences between any two values are relative and unequal rather than quantitatively equal (see March 1934: 20, for an effort to develop a scale with values intermediate between those of the Mohs' scale minerals). There is very little difference in microhardness between minerals 3 (calcite) and 4 (fluorite) in the scale, for example, but a great difference between 6 (orthoclase) and 7 (quartz). For this reason, although hardness measurements yield a numerical result, they cannot be used with statistics designed for interval scales, such as calculation of a mean. Instead, the descriptive measures common to ordinal scales, such as modal and median values, must be used to characterize the hardness of a collection.

In general, interpreting the results of hardness tests requires caution, partly because the surfaces of pottery—especially hand-built, low-fired pottery—are likely to be highly variable, but also because the results of different tests may not correlate well with each other. For example, indentation tests are associated with the hardness of the mineral components of a composite (crystalline) material, whereas abrasion tests measure the strength of the bonds holding the grains together. Similarly, scratch hardness is not likely to be useful on rough surfaces, because the movement of the mineral will tend to tear out individual grains rather than actually penetrate the surface.

Apart from firing, the most important determinants of strength are textural and microstructural attributes. A strong ceramic is one with inclusions in a range of sizes and angular shapes. Very fine particles in the body enhance strength in relatively high-fired ware because they sinter and fuse more readily than do coarse ones, thus beginning vitrification and formation of a homogeneous glassy phase at lower temperatures. Although no specific quantity of inclusions can be specified for maximum strength, because this varies with individual bodies, the optimum amount of quartz added to strengthen a (high-fired) clay body has been suggested to be 25% by weight (Kennard and Williamson 1971; Robinson 1968a).

The strength of a fired ware may be decreased by contrary conditions. Inhomogeneities in the body—resulting from uneven drying, particle-orientation effects, thickness, shape, density—can cause stresses that may weaken the ceramic and increase the risk of cracking or failure in firing or use. Similarly, firing a body containing calcium carbonate to temperatures between 750°C and 1000°C may weaken it because of the rehydration and expansion of CaO, unless the particles are extremely fine.

Materials scientists have devoted considerable attention to the performance characteristics of commercial ceramics and these approaches can be used to understand the strength, durability, and failure of ancient vessels. Strength is usually analyzed in terms of a material's resistance or response to the various mechanical stresses that may act upon it. Two "intrinsic properties" of ceramic materials are related to strength assessments: the modulus of elasticity and Poisson's ratio. Strength itself, particularly

flexural strength, is usually given by the modulus of rupture, *T*. Although most of the technical materials literature treats high-fired industrial ceramics and bricks, the tests also provide a variety of data, concepts, and techniques that can, with due caution, be applied to ancient low-fired pottery (Vandiver 2001).

Size and shape of the piece appear to matter, as seen in simulated service testing of tableware with various design attributes. One engineering study, which examined the rims of vessels as a significant source of fracturing leading to failure or breakage, found that chipping resistance varied closely with thickness and profile or cross-sectional shape (Dinsdale et al. 1967: 374–86). Thicker pieces and pieces with flat or squared cross sections had greater resistance than thinner pieces and those with pointed and/or rounded contours.

Similar relations may or may not be important in assessing the serviceability of low-fired archaeological ceramic vessels. To analyze such pottery, larger numbers of samples or broader tolerances may be necessary, depending on the circumstances. Shepard (1936: 434–35) manufactured more than one hundred clay test pieces and fired them to temperatures comparable with those used for Pueblo pottery to test the effects of shape and thickness on transverse breaking strength. She found that in those test samples both thickness and curvature had negligible effects on strength, the thickness variants differing less than 15% from the group average and curved pieces only 5% from flat pieces (see also Neupert 1994).

18.3 Permeability and Porosity

Three related properties affecting vessel use, permeability, porosity, and density, are determined by composition, including microstructure, and fabrication. These properties are not equivalent, but they are closely related in their constraints or actions.

Box 18.2 Measuring Stresses and Strengths

The response of a ceramic to various mechanical and physical stresses can be measured in different ways (Grimshaw 1971: 857–61). This means that the strength of the material in resisting each can be calculated and the particular characteristics of the resulting fracture patterns after failure can be identified. These tests measure the stressing forces as well as various aspects of the material's (i.e., a ceramic's) strength.

- Tensile stress is calculated as the amount of force applied divided by the area of cross-section of the piece in the plane at which fracturing occurs; tensile strength is the stress at which fracturing occurs. In testing tensile strength, the result should be independent of the size and shape of the piece.
- Testing for compressive strength is closely tied to the rate at which the stress is applied as well as to the shape and particle size of the object being tested. Test pieces should be at least ten times the maximum dimension of the largest grains present in the material, and small test pieces often give a larger scatter of values because of compositional heterogeneity. Failure under compressive forces is usually evidenced as a shear fracture occurring at an angle of approximately 45° to the direction of force.
- Measurement of transverse or bending strength (the modulus of rupture, T) is fairly straightforward: the test piece, which must be flat, is supported at one or more points (usually it is rested upon two or more points), then downward force is applied to the upper surface. The lower layers, bending down between the supports, are thus in tension, and fracture begins by tensile failure at the lower surface and moves into the interior of the body. Calculation of the modulus of rupture takes into consideration the length (l), width (b), and thickness (t) of the piece at a given force (W), as $T = 3Wl/2bt^2$.

Most of these performance tests are at least partially dependent upon the size and shape of the test piece; this is particularly true of the transverse (bending), torsional, impact, and compression tests (see Grimshaw 1971: 844).

In addition, standard procedures (e.g., American Society for Testing and Materials) generally recommend testing multiple specimens, uniform in size and thickness; for example, for transverse breaking strength it is recommended that ten specimens be tested. Any test values varying more than 15% from the average should be discarded, and if more than two are discarded the test should be repeated. Tests of low-fired archaeological pottery may yield a wide scatter of values because of its inhomogeneities, curvature, and fragmentary nature.

18.3.1 Pores

Virtually all ceramic materials contain pores or voids as one of their phases. Pores are spaces between or within the solid particles. Their size and shape are influenced by the size and shape of particles in the clay body and their arrangements. Pores may be characterized by their size, shape, and position in the ceramic as either open or closed (Grimshaw 1971: 417, 419, after Washburn 1921: 918; see also Brewer 1964: 91–93).

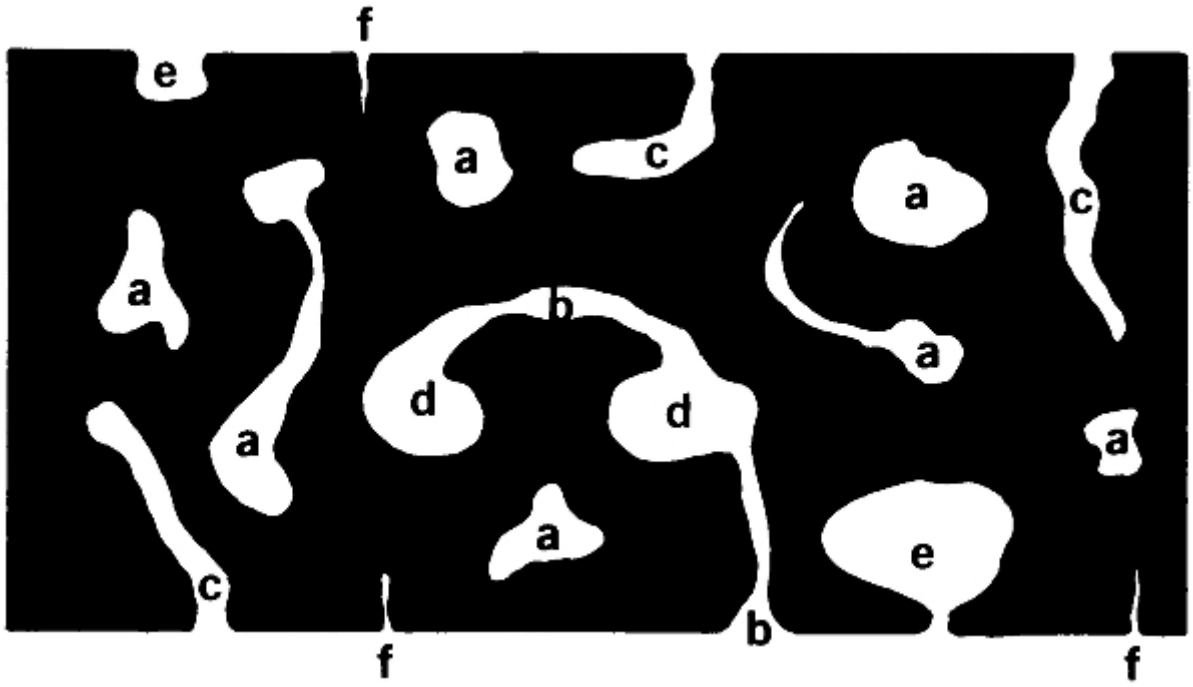

Figure 18.3 Various kinds of pores: *a*, closed pores; *b*, channel pores; *c*, blind-alley pores; *d*, loop pores; *e*, pocket pores; *f*, micropores. After Washburn 1921: 918, and Grimshaw 1971: fig. VII.21.

Open pores are open to the exterior surface from inside the wall of the vessel. They may be formed from the packing of individual grains in the body, from the escape of water or gases during firing, and from the cracks that develop during drying and firing, with concomitant shrinkage or expansion (Grimshaw 1971: 419). In traditional pottery these processes may be increased by the burnout of organic material in the clay or by the decomposition of carbonates. Open pores are of several kinds (fig. 18.3):

- Pocket pores, which often have a narrow aperture or neck;
- Micropores, which are too small to contain liquid under normal pressure;
- Loop pores, two interconnected pores;
- Channel pores, which connect two pores or a pore and the surface;
- Continuous pores, which extend from one surface to the other; and
- Blind-alley pores, which extend from the surface without other connections.

Closed or sealed pores may occur naturally in the body of the ceramic without any exterior connections, or they may develop during heating as open pores become sealed through shrinkage and vitrification.

Pores are usually irregular in shape, but different forms are characteristic of different kinds of particles and ceramic materials. In high-fired, fine-textured products, pores may be isolated, spherical, and frequently so tiny that they can be measured only in micrometers (see, e.g., Grimshaw 1971: 426, 427). Porosity and permeability are negligible. In low-fired pottery, by contrast, pores often can be seen and measured with the naked eye. Fibers, seeds, and other macrobotanicals usually burn out, leaving voids that are casts or molds of the original (see Reid 1984). The remaining charred or

incompletely oxidized organic material may act to reduce porosity, increase the strength of very coarse or sandy pastes, and serve, in effect, as a charcoal filter.

18.3.2 Permeability

Permeability refers to the penetration of a fluid (water, air, gases, smoke) from the surface of a vessel into the wall through open pores. This permeation may be outward seepage of a liquid contained inside the vessel or the movement of exterior moisture or smoke (etc.) from the atmosphere or the resting surface to the interior. Permeability depends on the kind, size, number, and distribution of open pores, the presence of cracks and flaws, differences in pressure and temperature on each side of the piece, thickness of the piece, nature of the fluid, and, in testing, the duration of the measurement (Grimshaw 1971: 436).

Although clearly related to porosity, permeability is strictly a function of the various types of open pores and does not register the presence of closed pores. For this reason, modification of the interior or exterior surface of a clay vessel, or both, has a significant effect on permeability and its related properties by increasing its density or acting as a barrier to penetration. A pot can be porous but at the same time relatively impermeable.

Glazes are the most obvious preventer of penetration of liquids, but in times and areas of the world where glazes were and are not used by traditional potters (e.g., much of the pre-Columbian Western Hemisphere), a slip or even burnishing the surface can reduce permeability to some degree (Birmingham 1975; Henrickson and McDonald 1983: 633). Postfiring treatments of porous vessels, attested ethnographically, have the same effect. These are coatings of lime water, resin, vegetal material, or some other organic substance applied before use in cooking or storing liquids. These treatments can retard the penetration of liquids by creating a dense surface of fine and, in the case of burnishing, compacted particles. They have an additional advantage of making cleaning easier: they often cover the interiors of bowls and jars and extend over the lip and partway down the exterior shoulder or neck. This lessens the penetration of drips and splashes into the vessel walls. In cooking vessels, organic resins do not decrease the usefulness of porosity in reducing thermal stress. It is not clear if these coatings might survive burial to be registered in porosity/permeability analyses of archaeological pottery.

18.3.3 Porosity and Density

The volume of pores within a ceramic body determines its porosity and density:

- Porosity is a measure of the volume of pore spaces that allows a substance to move through the wall once it has penetrated either surface.
- Density, the mass of an object per unit volume, may be loosely considered as the inverse of porosity: a dense paste is low in porosity. Specifically, it is usually considered as either:
    - Bulk (apparent) density, which includes porosity; or

· Theoretical density, which is solid phases only.

Porosity and density are largely manipulated by the steps of initial clay preparation: the amount, size, and shape of inclusions present in the paste, and the care exercised in wedging. Among the factors influencing porosity and density are the sizes, shapes, and packing of solid phases (particles), the specific constituents of the clay-body mix, and the treatment to which the material was subjected during manufacture. The overall porosity of a vessel also can be affected by the porosity of inclusions (Grimshaw 1971: 420).

Before a clay body is fired, almost all porosity exists as open pores. During the early part of the firing sequence porosity increases as organic matter and volatiles are burned out of the system. Porosity reaches a maximum at about 800°C and may be maintained at well above 30% until temperatures as high as 1000°C are reached (Grimshaw 1971: 816). In general, however, above 800°C porosity declines as the mass starts shrinking and densifying, processes accelerated by sintering and vitrification. Many open pores are eliminated or transformed into closed pores; open pores are usually eliminated when porosity is reduced to about 5%, and the volume fraction of closed pores increases (Kingery et al. 1976: 521).

Porosity affects a wide range of properties of a ceramic, including strength, resistance to spalling, resistance to mechanical and chemical erosion, and refractoriness (Grimshaw 1971: 420–21; Kingery et al. 1976: 518, 521). In addition, high porosity can increase thermal insulation: the air space resists the passage of heat, especially if the voids are discontinuous.

Box 18.3 Measuring Porosity

Porosity is usually described as either true or apparent:

- True porosity (also called total porosity) refers to the total proportion of the bulk volume occupied by pores, both open and closed.
- Apparent porosity includes only the larger open pores connecting to the surfaces and excludes closed pores and micropores. Apparent porosity is often related to absorption (which is, however, a weight rather than a volume measure) and permeability.

In determining the porosity of a ceramic, the shape, size, and number of pores are of interest as well as their volume. The shape and size of pores are measured by a variety of microscopic methods, including standard and polished thin sections and electron microscopy. Thin sections allow a view of the range of sizes, shapes, orientations, and positions relative to other phases in the ceramic. The volume of pore space can be estimated through point counts or areal analyses, done more easily with automatic integrating microscopes.

Direct measurement of volume porosity is restricted to apparent porosity (or absorption) rather than total porosity, because absorption methods cannot gain access to the sealed pores. For this reason, total porosity is calculated in terms of density. The bulk or apparent density is a ratio of total weight to external volume and is thus a function of both total porosity and true density. Because sealed pores often make up a portion of the volume, true density is the total weight divided by the total volume of solids. The formula for calculating total porosity is expressed as a ratio of bulk density (d_b) to true density (d_t):

$$P_t = \frac{d_t - d_b}{d_t} = 1 - \frac{d_b}{d_t}$$

The total porosity of commercial ceramics varies from less than 1% to as much as 90%. Earthenwares (most directly comparable to archaeological pottery) vary from 20% to 25%, stonewares from 0.5% to 2.0%, and bricks from 3% to 73% porosity, but 12% to 30% is the typical value (Grimshaw 1971: 820).

Apparent porosity is usually measured by liquid immersion, water absorption, or mercury intrusion porosimetry techniques. In all these procedures, test samples of the ceramic are thoroughly dried in a drying oven at 105–110°C and then weighed (W_1). In the liquid immersion method, the dried test piece is placed in a vacuum chamber that is evacuated, then enough liquid is introduced to cover the sample. The liquid permeates the pores under vacuum conditions, and the piece is then removed and reweighed (W_2). Its weight when immersed in liquid is also determined (W_3). The percentage of apparent volume porosity is determined by the following equation:

$$P_A = \frac{W_2 - W_1}{W_2 - W_3} \times 100$$

The water absorption method is a variant of the liquid immersion technique, except that instead of using a vacuum, the dried and weighed (W_1) piece is placed in a suitable container, covered with water, and boiled for five hours. At the end of that time the container is removed from the heat and

the piece is cooled to room temperature while still immersed in water. When cool it is removed, wiped dry of surface water, and reweighed (W_2).

The distribution of pore volume according to some measure of pore size yields much more information than a simple parameter such as apparent porosity and is often used in studies of ceramic processing. Such information may be presented as a cumulative graph showing the proportion of pores smaller or larger than a given pore size (e.g., see fig. 23.1).

18.3.4 Additional Considerations

Measurements of porosity permit better understanding of the use-related properties of a ceramic and inferences about the compositional and manufacturing design decisions it represents. In drawing these inferences it is important to recognize several differences between low-fired traditional pottery and the high-fired commercial ceramics more commonly tested by these methods. The object of commercial ceramic manufacture is to fire a formed piece to a temperature high enough to mature body and glaze and decrease porosity. Porosity is often reduced to 2–3% or less in the bisque stage, and for some bodies it is desirable to have it less than 1% (table 18.2). Simultaneously, reducing the time and temperature of firing to a minimum saves fuel costs.

Although most of the bonfire-fired terracottas or earthenwares common in antiquity would be considered underfired by the standards of the contemporary ceramics industry, owing to their inhomogeneous composition and porosity, they are suitable for their intended uses. People accustomed to eating food cooked in traditional earthenwares claim the taste is superior; a porous jar allows stored water to cool by evaporation. Thus not being high-fired to a glassy, homogeneous phase increases the perceived and desired serviceability of these low-fired wares. Nonetheless, a measured degree of porosity may or may not have been intended in a final product.

Table 18.2 Porosity of Some Fired Ceramic Products

Product	Porosity (by volume %)
Stoneware	0.5–2.0
Hard porcelain bisque	3–9
Semiporcelain bisque	13–23
Chinaware bisque	2–11
Earthenware bodies	20–25
Tiles	3–18
Building bricks	10–35
Porous fireclay bricks	up to 60
Saggars	10–40

Source: After Grimshaw 1971: table XII-XVII.

In addition, after centuries or millennia of burial, a permeable and porous vessel may have been penetrated by substances, such as salts or various minerals, that were deposited or that crystallized in the vessel pores (see Courtois 1976; Magetti 1982; also Franklin and Vitali 1985). What is being measured, therefore, is neither true porosity nor apparent porosity, but a likely reduced residual porosity, which may or may not approximate that of the vessel at the time of use.

Permeability, and therefore apparent porosity, can vary in different parts of a commercial ceramic body because of fissures, holes, and inhomogeneities (Grimshaw 1971: 438). These irregularities are even more likely to be present in traditional hand-built pottery. Because permeability is often used as a measure of apparent porosity in unglazed (and probably even in some slipped) pottery, this known variability casts further doubt on the significance of the measurement, especially if used comparatively. Additional variations in porosity/permeability of hand-built pottery may result from the techniques of manufacture, such as greater stroking, thinning, scraping, or burnishing of certain areas of the vessel (e.g., a rim), which may alter the size and number of open and closed pores.

18.4 Cracks and Failure

Ceramics typically fail because of brittleness: low elasticity and low tensile strength. But this can be understood in far more specific terms. Fracture failure of brittle materials such as ceramics generally starts with cracks, typically preexisting flaws and microcracks. These tiny flaws may be present in the microstructure, specifically in the contacts between phases and in the kinds and sizes of crystals, as a result of local or internal stresses that may have begun during forming, drying, or firing. These microcracks and flaws arise from the mechanics of forming and from surface imperfections, and are likely to penetrate well into the body (Stokes 1968: 380). In hand-built, low-fired wares, such flaws can result from coiling, molding, scraping, burnishing, and so forth, and from the stresses of drying, particularly if the paste lacks green strength. Firing stresses include phase transformations and differential thermal expansions or contractions (Chu 1968: 854).

Microcracks and flaws in a fired ware concentrate tensile and other stresses at their tips. When this local stress exceeds a critical value, the microcrack starts to grow. Porosity plays a role, in that some pores may act as flaws and propagate the crack, particularly under tensile forces or repeated stresses such as heating-cooling cycles. At a certain point the crack becomes large enough that the propagation process is catastrophic: the piece fractures and fails.

Porosity thus has considerable consequences for the strength of a ceramic. Depending on their shapes and orientations, pores can be viewed as stress concentrators. On the other hand, rounded pores may blunt the crack or, like individual crystals, interrupt its path and prevent its continued propagation. But even small volume fractions of porosity (e.g., 10%) in a brittle ceramic can reduce strength by as much as half (Hasselman and Fulrath 1968: 345).

The fracture strength of the ceramic depends on the sizes and orientations of any preexisting flaws, on how subsequent crack propagation takes place once the critical stress is exceeded, and on inherent properties of the material. Given that flaws, weaknesses, and cracks are prevalent throughout the body of hand-built, coarse-textured, and low-fired ceramics, the question becomes one of understanding the characteristics that contribute to or restrain the propagation of cracks. Different forces seem to affect the relation of porosity to strength in vitrified compared with crystalline low-fired ceramics. Strength decreases with increasing porosity, because “pores act as brittle phases of zero strength” (Chu 1968: 852). The processes are complex and depend at least in part on phase relations and the number, size, and shape of pores (see Kingery 1960: 598; Grimshaw 1971: 836, 894; Hasselman and Fulrath 1968: 372, 373).

Most of the strength testing in the materials industry centered on high-fired (vitrified) ceramics or materials that are relatively homogeneous in composition, particularly whitewares, porcelains, and bricks. Lower-fired vessels are clearly less durable, at

least in comparison with normal commercially fired tableware. In one test identical sets of earthenware service pieces, differing only in firing (normal fired versus “easy fired”) were used for four weeks in an industrial canteen. At the conclusion of the test, 68.6% of the easy-fired pieces had suffered damage, with a damage:use ratio of 1:9; in contrast 28.9% of the normal-fired earthenware suffered damage and had a damage:use ratio of 1:54 (Dinsdale et al. 1967: 402–3).

18.5 Relations to Use

There is little to discuss about how the physical properties of hardness and strength relate to pottery use, because these properties are virtually always desirable and contribute to long use-lives. Although it is difficult to conceive of specific circumstances where a soft, weak vessel would be an advantage today, clearly low-fired, fiber-tempered "softwares" were sufficient for the earliest pottery use requirements throughout much of the world for centuries or millennia (chap. 1). It is probably in processing foodstuffs and transfer (moving pots and their contents) that strength and hardness are most important. In processing, the contents of a vessel may be stirred, pounded, or ground, mechanically stressing the vessel and causing various kinds of attrition that may lead to eventual breakage. Transfer activities probably pose the greatest threat, because vessels frequently break—especially wet, slippery water jars—as they are being carried, and in this type of use mechanical strength is most valuable.

The relations between porosity/permeability and pottery use are complex, particularly with reference to heat and thermal stresses in cooking. Cooking can produce thermal stresses (placing the vessel in the fire) as well as mechanical ones (stirring the contents). Porosity can increase heat transmission and reduce thermal stress, but for cooking liquids there is a danger of seepage. Increasing porosity may be a more appropriate strategy for dealing with thermal stresses in vessels used for dry processing, such as toasting or parching.

Excessive porosity and permeability are not desirable in vessels used for long-term storage, particularly of liquids. Raised bases or supports on unglazed pottery may keep a leaky, porous serving or processing vessel from direct contact with a surface. Nonetheless, high porosity characterizes nonvitrified vessels, especially earthenwares: Jomon pots were found to lose about 10% of their liquid contents overnight (Kidder 1968: 14) and some Corinthian amphorae were permeable in nine to thirty-one minutes (Vandiver and Koehler 1986: 204). For relatively short water storage, porosity is often an advantage for evaporative cooling. After a time, however, minerals in the water seal the pores so the pot loses its effectiveness as a cooler, and it may then be switched to some other use such as cooking (Fontana et al. 1962: 80).

19 Thermal Behavior

> Unless ceramic studies lead to a better understanding of the cultural context in which the objects were made and used, they form a sterile record of limited worth.
>
> Matson 1965: 202

The behavior of a clay material at high temperatures or under conditions of temperature change is of concern in two situations: initial firing of the clay and use of the final vessel with application of heat, whether in cooking, metallurgy, or some other endeavor. In both situations heat causes most of the individual constituents of the ceramic body to expand, and on cooling they contract. This expansion and contraction can lead to internal stresses, particularly when common boundaries restrict free expansion or contraction. It is the response of the body to these thermal stresses that interests ceramists.

19.1 Thermal Properties

The thermal behavior of a material begins with expansion: materials expand as heat energy is applied because the heat increases the vibrational movements of the constituent atoms or ions. The movements increase in amplitude, expanding the crystal lattice of the material. Two intrinsic materials properties of ceramics are important to understanding this thermal behavior:

- Coefficient of thermal expansion: a measure of a material's increase in size in both linear (α) and volume (β) dimensions as heat is applied, expressed as the amount of change per unit per degree Celsius (table 19.1).
- Coefficient of thermal conductivity (k): the rate or ease with which heat passes through a material under a particular temperature gradient.

The expansion coefficient is a function of temperature: very rapid expansion at low temperatures gradually levels off with higher temperature, although the range over which this occurs varies among different minerals (see Kingery et al. 1976: 591–95). In solids the volume expansion is approximately three times the linear expansion. In liquids the expansion is greater: when water boils and becomes steam, for example, it expands in volume by a factor of 1600–1700: that is, one liter of water becomes 1600–1700 liters of steam. Thermal expansion may exert considerable pressure, which is what allows steam to power engines and causes a ceramic to rupture when water in the pores of a cooking pot is heated. The thermal expansion of some materials (fig. 19.1) is reversible—contraction occurs on cooling, and with subsequent reheating the expansion will recur—but in other cases the volume change may be permanent.

Table 19.1 Coefficients of Thermal Expansion of Some Ceramic Materials

Material	Coefficient of Expansion $\times 10^{-7}$
Alumina	81
Mullite	45
Silicon carbide	47
Electrical porcelain	60
Cordierite bodies	30
Steatite bodies	70
Dolomite bricks	110

Source: After Grimshaw 1971: table XII-X.

With respect to a ceramic body, its thermal properties, like physical and mechanical properties, are a function of microstructure. The relations among the phases of the ceramic—grains, any glassy material, pores, and their boundaries—are constantly in transition as part of the changing chemical and physical states of the ceramic on firing and cooling. During these processes, the microstructural system changes to minimize free energy and to approach thermodynamic equilibrium at the given conditions of temperature, pressure, and composition. True equilibrium, however, is rarely attained in actual ceramic bodies, even in high-fired wares, because the reactions involved take considerable time.

Most ceramics—particularly those of anthropological and archaeological interest—are composites of mostly crystalline materials, making it difficult to determine precisely the expansion of the body. Although the thermal expansion of a mass approximates the average of its constituent phases, individual minerals have different coefficients of expansion and these may vary with crystallographic direction (Grimshaw 1971: 790; Rye 1976).

With respect to thermal conductivity, transmission of heat through a solid body can be envisioned as a three-dimensional analogue of the propagation of a wave pulse along a guitar string when it is plucked; the vibrational states of the atoms act like the modes of vibration of the string. If the body is homogeneous on a scale smaller than the wavelengths, the waves are easily transmitted (metals, for example, are good conductors). However, grain boundaries, pores, compositional variations, and such can interfere with and scatter the waves, reducing the transmission of heat. The thermal conductivity of a ceramic is influenced by all these factors, compositional and microstructural, but porosity is particularly significant (Grimshaw 1971: 934–46).

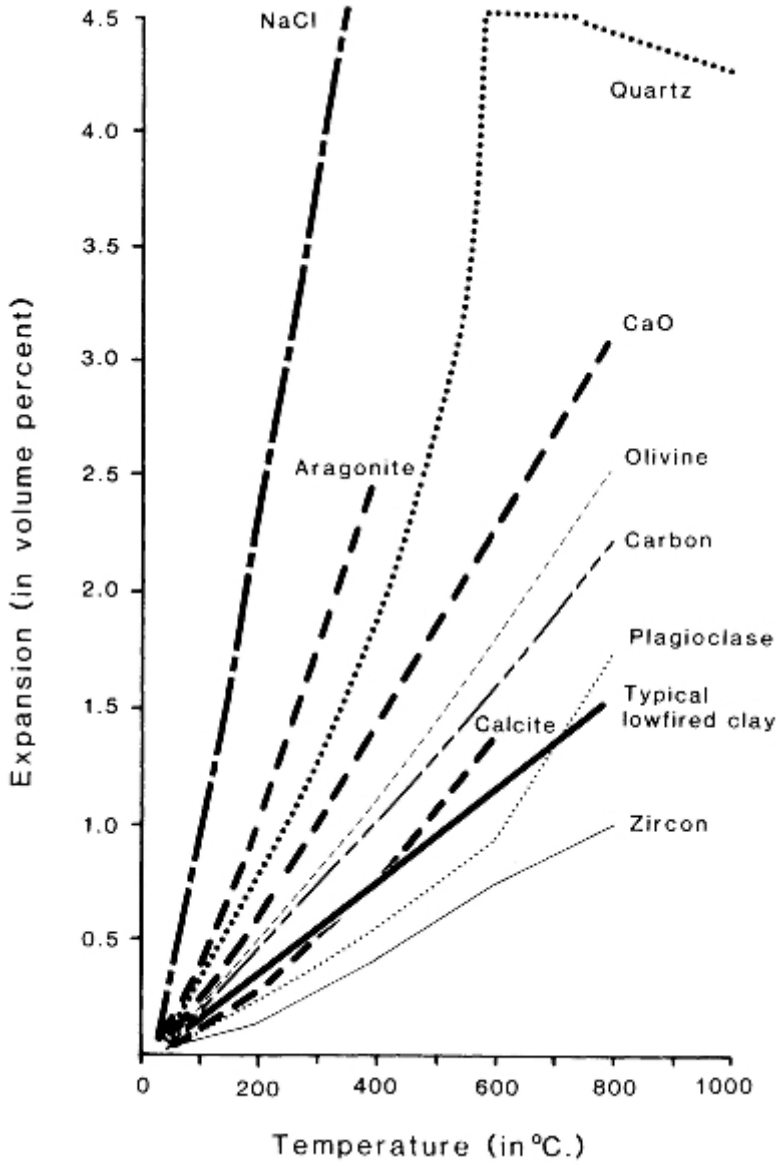

Figure 19.1 Thermal expansion of some common minerals. After Rye 1976: fig. 3.

The use-related ceramic property of heat conductivity or transmission can be considered in terms of its converse: insulation capability. Both are affected by porosity, because air (in pores) insulates better than does a solid. Pores, in other words, especially their kinds and sizes, determine how rapidly heat moves through them and through the ceramic body by convection and radiation. A material with closed pores, even if there are a lot of them (high porosity), will transmit heat more slowly and be a good insulator but a poor conductor (Grimshaw 1971: 936, 947). The relations between porosity and conductivity were investigated in experimental firings of homogeneous (high-fired, vitrified) bodies with closed pores: specimens with 50% porosity had about one-sixth the conductivity of denser samples (Coble and Kingery 1955: 37). Large, open, and connected pores, on the other hand, increase thermal conductivity and heat transmission because they permit hot gases to pass easily throughout the body

(Grimshaw 1971: 420–41, 937). This also reduces thermal gradients. Thus a ceramic with these properties, such as a low-fired, multiphase body, will make a good cookpot, conducting heat from the cooking fire through the walls to the contents. It is a poor insulator.

19.2 Thermal Stresses and Shock

Thermal stress refers to the forces—primarily compressive and tensional—that arise in a clay body, fired or unfired, when it is subjected to changes in temperature (see Chandler 1981; Crandall and Ging 1955; Davidge and Tappin 1967; Hasselman 1969; Kingery 1955). These stresses may arise from various causes:

- A change in the ambient or uniform temperature of the material, such as a change from room temperature to 250°C, which causes minerals to expand on heating and contract on cooling.
- Temperature gradients within the body of the ceramic: exterior surfaces may be hotter or cooler than the interior vessel walls or one side may be hotter or cooler than the other.
- Sudden or dramatic raising or lowering of the temperature, which causes thermal shocking.
- Cumulative thermal fatigue: the delayed failure of a ceramic caused by gradual weakening through repeated cycles of thermal stressing.

Thermal stresses are caused by restraints on free expansion and contraction of the phases in the ceramic. On heating the individual crystalline components expand at different rates, but are constrained by adjacent grains or phases; all are constrained within the finite bounds of the ceramic body. This results in compressive stresses on the surfaces and tensile stresses on the interior. On cooling the reverse is true, with more rapid contraction on the surfaces causing tensile stresses, while the interiors suffer compressional stress. Shear and transverse stresses may also be present.

Thermal shock results from the excessive stresses brought about by differences in the thermal expansion of its components. Sudden temperature changes and expansion differentials may bring about rapid compressive and tensile stresses that cannot be accommodated instantly. When these stresses exceed the strength of the body, fracturing or shattering may result.

Some thermal stresses can bring about complete failure of the ceramic without the suddenness of thermal shocking. Dunting, for example, refers to the cracking that occurs either while ware is cooling from its original firing (especially if it is cooled too rapidly) or from expansion of quartz between 400°C and 600°C on reheating bisque ware (Lawrence and West 1982: 287). Dunting cracks typically occur at the rim of vessels as a result of tensile stresses (Rye 1981: 114). Thermal fatigue is another example of this phenomenon.

Thermal stresses have many sources. For example, exposing an unfired clay body to cooling air currents may evaporate water from the surface too fast, leading to cracking and warping. When the ambient temperature is suddenly raised, the clay body expands rapidly as water and other gases immediately volatilize and the clay constituents expand microscopically with heat. Such stresses may occur in firing a vessel if it is not preheated, if the temperature is raised too rapidly, or if cold air currents come into contact with the hot ware during firing or cooling. In addition, any inhomogeneities in the body—resulting from uneven drying, particle-orientation effects, thickness, shape,

density—can cause or exacerbate stresses that may weaken the ceramic and increase the risk of cracking or failure with temperature change.

19.3 Stress and Shock Resistance

Thermal stress resistance—the ability to withstand weakening, fracture, or spalling under conditions causing thermal stress or shock—is an important property of a durable ceramic body, unfired or fired. Clay bodies with high resistance to thermal shocking are able to suffer sudden temperature changes because their components have low rates of expansion (low thermal expansion coefficients). Ceramics' refractoriness, or ability to withstand extremely high temperatures, has contributed to the wide range of uses, from ancient and modern cooking to jet engines.

At one extreme in contemporary commercial ceramics, cooking vessels with low coefficients of thermal expansion (from 2.0 to 4.5 × 10^{-6} per °C; Norton 1970: 357–58) include ovenwares and flamewares (such as CorningWare™), which can be placed on a range or moved from a freezer to a hot oven without shattering from the abrupt temperature change. These wares are manufactured according to special formulas and usually include only small amounts of clay and quartz. The reason for reducing these materials is that discontinuities in the expansion behavior of SiO_2—especially quartz and cristobalite—lead to stresses that can cause thermal shock fractures. The discontinuities of quartz (the **α**–**β** transition) are above normal oven cooking temperatures, so the major problem in ovenware cracking is the high-temperature mineral cristobalite, which undergoes a transition on cooling at low temperatures of 200–270°C. Thus materials that introduce quartz or induce formation of cristobalite in the body should be avoided if a ware is to resist thermal shock. Chemical formulas for resistant wares may contain large amounts of cordierite (a magnesium aluminosilicate) or lithium minerals (e.g., spodumene), which have extremely low coefficients of thermal expansion (table 19.1; Lawrence and West 1982: chap. 15). Another mineral added to reduce thermal expansion—and sometimes found in non-industrial pottery—is steatite or talc, a hydrated magnesium silicate.

Although past and present non-industrial village pottery may not be able to withstand such dramatic temperature transitions as modern wares that move from freezer to stovetop, a fundamental use of these vessels has always been cooking. Such usage often entails placing vessels directly on or in a fire with some confidence that they will not break. Traditional terracotta and earthenware pots typically are able to withstand this thermal shocking not because of their optimally engineered chemical compositions, but because they are low-fired, porous, and coarse in texture. Because they are low-fired, they do not attain a rigid, glassy structure and instead can expand and contract as necessary. Also, their loose, open texture allows whatever expansion does occur to be accommodated by the pore spaces and prevent any cracking that may take place from extending too far.

Box 19.1 Measuring Thermal Shock Resistance

Thermal shock resistance can be measured as the maximum sudden temperature change the ceramic can withstand without cracking or weakening (Crandall and Ging 1955: 44). Testing requires establishment of a temperature gradient (e.g., by quenching specimens in water from successively higher temperatures) and measuring some property to detect the onset of failure, such as a drop in strength or a fracture (see Coble and Kingery 1955; Davidge and Tappin 1967). The temperature at which this change occurs, Δt_f, is taken as a measure of thermal shock resistance. Another procedure uses simulated service tests, which subject a large batch of identical pieces to testing conditions simulating those of actual use. This is especially useful for testing how shape affects thermal stress resistance.

The various properties that influence resistance to the initiation of fracture, for instance, are illustrated with the following equation:

$$\Delta t_f \approx R' = \frac{kS_t(1-\nu)}{E \cdot \alpha}$$

In this equation R' is the "thermal stress resistance factor," k is the thermal conductivity of the material, S_t is the tensile strength, ν is Poisson's ratio, α is the coefficient of thermal expansion, and E is the modulus of elasticity (see Kingery 1955; also Crandall and Ging 1955; Davidge and Tappin 1967: 407; Grimshaw 1971: 949).

The susceptibility or resistance of a ceramic body to thermal stresses is conditioned by a number of factors (see Grimshaw 1971: 948–49; Kingery 1955: 6, 8). Some can be manipulated during manufacture by modifying either composition (particularly temper) or design, whereas others are largely fixed, constrained by the nature of ceramic materials in general. Besides the obvious role of temperature itself (absolute and variable), the significant variables of thermal stress resistance can be divided into three categories: the intrinsic material properties of ceramics, the microstructural features of the ceramic body, and the design features of the shaped ceramic piece.

19.3.1 Intrinsic Properties

Many of the major factors influencing thermal shock resistance are its intrinsic properties, but not all of these can be manipulated by potters to increase thermal stress resistance. This is especially true of the modulus of elasticity (E) and Poisson's ratio ($\boldsymbol{\nu}$). Ceramic materials are susceptible to thermal failure partly because they respond to temperature changes by creating large stresses, which cause cracking. The quantity $E/(1 - \boldsymbol{\nu})$ is a measure of these stresses.

The coefficients of expansion of the individual components are significant because of the danger of "thermal dimensional mismatch," a condition in which the differential expansion of some minerals creates large internal stresses that exceed the body's

capacity to adjust. High coefficients of thermal expansion contribute to low resistance to thermal shock. This mismatch is particularly important in terms of mineral materials added to the clay as temper: ideally these additives should have low coefficients of thermal expansion or coefficients that match those of the fired clay as closely as possible (see Bronitsky and Hamer 1986: 96–97; Lawrence and West 1982: 223; Rye 1976: 116–17).

The relations between clay and temper as they apply to thermal behavior, however, are complicated. On the one hand, because mineral additions "dilute" the concentration of a clay in a given body, they also diminish the thermal mismatch that occurs in the body during the critical dehydroxylation stage of firing, thereby reducing cracking (Robinson 1968b: 550–51). On the other hand, because most of the materials in polycrystalline ceramics are not isotropic, "anistropic thermal contraction on cooling from the fabrication temperature leads to the development of internal residual stresses" (Stokes 1968: 381).

High thermal conductivity is also a factor in resistance to thermal stress. Because ceramic materials generally are not good conductors (compared with other materials, such as metals), they transmit heat slowly and are prone to develop strong thermal gradients. Thus characteristics that increase conductivity will also reduce thermal stress. High thermal conductivity is especially desirable for reducing stresses during cooling (Kingery 1955: 11).

19.3.2 Microstructure

Microstructural features are perhaps most important to thermal stress resistance, in large part because they can be controlled by the potter. The chief microstructural properties of interest are particle size and porosity.

Fine-grained ceramic materials have more grain boundaries than coarser bodies, so they have greater thermal resistance and lower conductivity; they slow the transfer of heat through a body and are likely to give rise to thermal gradients. On the other hand, smaller grain size increases the fracture strength of polycrystalline ceramics (Stokes 1968: 381). Also, the smaller the particles the less the effect of thermal mismatch on some important constituents of ceramic bodies, such as quartz (Robinson 1968b: 550–51). This finding, however, generally pertains to high-temperature firings, where the quartz inversions can be particularly serious.

Porosity is of considerable significance in the thermal stress resistance of a ceramic, but its role is complex and sometimes equivocal (see Coble and Kingery 1955: 33–34, for a review; also Buessem 1955). In general, increased porosity in a body reduces thermal expansion stresses because voids interrupt the linear and volume continuities between the components (Grimshaw 1971: 791, table XII-VII): crystals can expand into voids without exerting pressure on surrounding grains. This is doubtless an important

reason why the expansion of quartz and other constituents of low-fired bodies creates little stress: the voids absorb the strains.

But the kinds of pores that exist affect thermal properties: in experiments, the thermal stress resistance of specimens with 50% porosity in closed pores was about one-third that of dense samples (Coble and Kingery 1955: 37). Such materials, especially if the pores are small, will be good insulators (Grimshaw 1971: 936, 947); they will conduct heat more slowly, but will also maintain thermal gradients, thereby lowering resistance to thermal stresses. Large open pores, by contrast, will increase conductivity and resistance to thermal stress, while also reducing thermal gradients.

Pores may also prolong the serviceability of ceramic wares because they inhibit the propagation of cracks and fractures that form from thermal stresses. On the other hand, porosity may help bring about the gradual weakening and loss of strength characteristic of cumulative thermal fatigue (Lawrence and West 1982: 225–26).

19.3.3 Shape and Design

Ceramic design must consider not only composition, but also size, shape, thickness, and surface finish, all of which are important in thermal stress resistance.

Several studies have investigated the relations between the size and shape of test vessels and their thermal fracture characteristics (e.g., Baroody et al. 1955; Crandall and Ging 1955). The larger the vessel, for example, the thicker the walls are apt to be and the greater the thermal gradients and stresses (Kingery 1955: 9). Generally, thinner pieces are more thermally resistant than thicker pieces (Brody 1979: 11; Van Vlack 1964: 117–65), because the increased conductance (conductivity divided by thickness) reduces the thermal gradient. Regardless of the absolute dimensions, it is advantageous for the walls to be of uniform thickness, because thicker areas have a more pronounced gradient than thinner ones and localize maximum stresses on heating and cooling (Kingery 1955: 10). Similarly, edges, corners, and thickened areas are particularly vulnerable to thermal fracturing. In simulated service testing (e.g., Amberg and Hartsook 1946), vessels surviving experimental conditions of thermal abuse had more gently rounded contours (see also Rye 1981: 27) and raised bases, which prevented direct contact with the heat source. In addition, a thickened "bead lip" reacted poorly to heating, but a raised foot was found to be an advantage.

With respect to surface finish, two features are primary: evenness of the surface and the presence of a glaze. Smooth surfaces are important because minor surface imperfections and cracks introduced by shaping may be propagated below the surface with heating and cooling (Stokes 1968: 380). With repeated temperature change their cumulative effect will be to reduce strength, although this may be minimized by factors of porosity. Burnishing or applying a slip may reduce this problem.

A glaze may either increase or decrease a ceramic body's resistance to thermal stress, depending on the degree of mismatch between the expansion coefficients of the

two materials (see Grimshaw 1971: 954; Kingery 1955: 11–12; Lawrence and West 1982: 179–85; Rhodes 1973: 241–43). On heating, the critical stresses are in the interior and are either shear or tensile, whereas on cooling they are tensile surface stresses (Kingery 1955: 12). If severe, these stresses will lead to crazing of the cooled glaze (see fig. 7.2). However, a glaze may act as a buffer on the body, decreasing the rate of heating and cooling at the surface and hence the thermal shock or stress on the body. Furthermore, glazes with about 10% lower expansion than the body of the ceramic will provide a slight surface compression and actually increase its strength (Kingery et al. 1976: 610; Lawrence and West 1982: 182; Rhodes 1973: 242).

19.4 Modifying Thermal Behavior

For practical purposes, the thermal behavior of a ceramic essentially comes down to a balance between the needs for conductivity and insulation, which are inverse properties. Different degrees of thermal conductivity are desirable for different purposes, depending on a vessel's use with heat.

The most commonly found earthenware vessels in antiquity and modern times are cooking pots. These should have high conductivity to transmit external heat rapidly to their contents, although this might be accompanied by less thermal stress resistance. Vessel shapes should, in principle, be rounded, without corners or angles where moisture collects and thermal gradients lurk, and thin-walled to let liquids convert to steam rapidly without buildup in the body. Thermal stresses arise as a ceramic and its contents are heated, but they may actually be more severe in cooling because tensile stresses develop on the exterior, especially when the vessel is resting on a colder surface (Amberg and Hartsook 1946: 451).

With respect to porosity, it has been suggested that for vessels used in cooking at temperatures of 300–500°C, the optimum pore size would be 7–9 mm, based on the size and density of packing of the mineral grains (Rye 1976: 114), although this is clearly unsuitable for actual practice. The porosity of vessels used to hold and cook liquids for any length of time can be a problem, however, because of seepage. Liquids boiled in porous vessels will seep through and rapidly evaporate, which has two negative consequences. First, the volatilization could cause the vessel to crack, but the danger can be reduced through some technical strategies of fabrication. Second, the water loss and evaporation represents heat loss, meaning that it will take longer to bring water to a boil (e.g., Harry et al. 2009).

Less common are vessels used with relatively higher and more sustained temperatures, such as refractory bricks and saggars associated with kilns, and crucibles and *tuyères* used in metallurgy. Refractory bricks should be good thermal insulators—and thus be likely to have low thermal conductivity and high thermal stress resistance—to minimize heat loss in kilns. Saggars and crucibles similarly need good thermal stress resistance, but, like cook pots, they should also have high conductivity for heating their contents. Both forms, along with *tuyères*, are relatively thick-walled for strength, as well as coarse and porous (e.g., Childs 1988, 1989; Martinón-Torres and Rehren 2009).

Thermal properties can be manipulated in many ways to reduce stresses in a ceramic intended for use with heat. One way is to adjust vessel morphology: the shape can be modified to eliminate angles and wall thickness can be decreased, because thinner walls lessen the stresses from thermal gradients (see Lawrence and West 1982: 226; Van Vlack 1964: 117–65).

Another way to modify thermal stress resistance is through the composition of the ceramic, particularly its mineral inclusions. The optimal solution would be to have inclusions (temper) with coefficients of thermal expansion similar to or less than that of the clay (fig. 19.1). Among such inclusions are grog (crushed sherds), calcite, crushed burned shell, zircon, rutile, feldspar, augite, and hornblende (Rye 1976: 116–17). Talc, used commercially in making saggars (Cardew 1969: 75, 159), can increase thermal shock resistance in amounts up to about 10% (Burnham and Tuttle 1945; Lawrence and West 1982: 224). In Uganda and elsewhere, potters may add asbestos-containing talc temper in their cooking pots and report that it "lengthens the life of the article, seemingly reducing the incidence of cracking on repeated domestic use" (Wilson 1973: 301).

A third way to improve resistance to thermal stress is to increase porosity, because pores provide spaces in the body that allow for sudden expansion of the grains. This alternative has its drawbacks, however, because repeated heating and cooling of porous materials causes them to gradually lose strength and suffer thermal fatigue (Lawrence and West 1982: 216–26).

In lieu of these other alternatives, in northwestern Pakistan the bases of cooking pots are periodically coated with a mixture of clay and sand to insulate the pot from thermal shock (Rye and Evans 1976: 25).

Some of the theoretical considerations about the relations between composition and thermal stress have been tested against the ethnographic record in the American Southwest (e.g., Plog 1980: 86–87). The results show that although potters may recognize that different kinds and sizes of temper affect the functional suitability of their products, some of their behaviors run counter to prediction with regard to thermal properties. Potters may use coarse temper to make vessels more porous, particularly for storing water, and clays intended for cooking vessels are often given special temper, but the Mohave use grog temper (with low thermal expansion) for all except their cooking wares. Both the Hopi and the Mohave potters use sandstone temper for cooking pots, while the Yuma use granite, but relative particle sizes are not specified. In Yucatán, crystalline calcite temper is most frequently used for cooking vessels, whereas attapulgite clay is generally used for water jars (perhaps with health benefits?), but this differentiation is not strictly followed (Thompson 1958: 113).

Perhaps the most complex set of adjustments is made by Shipibo-Conibo potters in Peru: different clay and temper combinations are used not only for different vessel functions (cooking versus noncooking) but also for different parts of cooking vessels (DeBoer and Lathrap 1979: 116–17). For example, ideally the bases of ollas are made of black clay tempered with two parts *caraipé* (plant silica ash) and one part grog, whereas the necks are made of red clay tempered with one part *caraipé* and two parts grog. In practice the composition is variable, although cooking vessels depart less from standard recipes than do eating and serving wares (DeBoer 1984: 540), perhaps because of thermal considerations.

Finally, surface treatment is an important modifier of the thermal properties of vessels: an uneven exterior has more surface area to absorb heat from a fire or to evaporate a liquid, as in salt-making (Charlton 1969: 75). Experiments have explored the influence of various surface treatments common in the Southwestern United States, particularly corrugation, on heating effectiveness, measured as the rate at which water temperature rises (Pierce 2005; Schiffer 1990; Skibo 2013: 49). Interior and exterior ceramic surface treatments do markedly affect heating effectiveness; indeed, there is an inverse relationship between surface permeability (as measured by initial absorption tests) and heating effectiveness. In addition, applying a resin or other substance to create an impermeable interior surface produced excellent heating effectiveness. Once the interior surface is made impermeable, exterior surface treatments have no appreciable influence on heating effectiveness. Corrugation increases thermal shock resistance but it did not, as once assumed, improve heating effectiveness under experimental conditions (Young and Stone 1990). It is not clear to what extent the findings on corrugation are generalizable to other kinds of texturing, such as striating or stamping.

Part 5

Research Questions and Problems: Interpreting Archaeological Pottery

> There are two ultimate aims in the interpretation of technological data. The first is to trace the history of the potter's craft; the second is to recover more accurately and in greater detail than is possible by other methods the evidence which pottery preserves of cultural development, contacts, and influences.
>
> Shepard 1936: 389

When Anna Shepard penned those words, she could not have had any idea of the kinds of analytical techniques that would be available in the early twenty-first century to pursue these aims. These methods provide a world of new ways to describe and characterize pottery by their composition and performance characteristics. Unfortunately, however, there is still a lag in the theories through which we can interpret these observations and integrate them into models of ancient behavior and society. Theory is by no means absent, but it has been developed further with respect to some topics than others.

The interpretive topics addressed in the six chapters of Part 5 exemplify the broadly integrative interdisciplinary approaches that are now commonplace in the study of pottery. The hybrid methods of archaeometry, experimental archaeology, and ethnoarchaeology join the instrumentation of the physical and materials sciences with the experiences of peoples practicing traditional technologies. These latter have called attention to a broad range of behaviors relating to pottery manufacture and use, including formation of the archaeological record. They also incorporate and benefit from the use of analogy, a long-debated practice often regarded with ambivalence (Ascher 1961; Binford 1967; Brown 2004; Hill 1998; Wylie 1985). But the methods and theories applied to analyses of pottery recovered in archaeological investigations have expanded well beyond the traditional analogical approaches of yesteryear. For example, study of pottery function and use-life is a late-twentieth-century development. Characterization studies of both the composition of a vessel and the use-related properties conferred by that composition allow archaeologists to pose and investigate new kinds of questions about materiality: the objects of daily life and the people who made and used them. These questions emphasize a broad range of behaviors relating to

pottery manufacture and use, and a framework on which to build broader interpretations.

The decorative motifs and styles of pottery, whether expressed through painting or plastic techniques (incising, molding, appliqué), yield insights into the lifeways of a people as well as their aesthetic perceptions and ideological systems. Complex issues of defining and interpreting style have moved well beyond simple interaction. The motifs and structures of pottery designs are seen as encoded behavioral information that can be used to infer varied social and cultural processes.

Unfortunately, similar models have not yet been developed for Shepard's "tracing the history of the potter's craft": interpreting the behavioral information encoded in the technological-compositional variables of pottery in terms of pottery production. As discussed in chapters 20, 21, and 22, complex questions of identifying both the location and organizational arrangements of pottery production remain somewhat murky, even though evidence can be adumbrated from multiple sources including the products themselves. Given the frequency with which an output- or product-based strategy must be adopted by archaeologists studying pottery production, it is all the more imperative to have comparable studies of the ceramic manufactures of contemporary potters.

20 Production I: Location

> Once the time and money have been invested in compositional analysis . . . the specimen is more than just another statistic; it holds promise for studies of design, morphology, function or other properties that may lie outside the primary research orientation.
>
> Bishop, Rands, and Holley 1982: 279

Pottery production refers to the socio-politico-economic arrangements through which pottery manufacture—the mechanics of forming, decorating, and firing a pot—are pursued. Production represents a point of intersection among humans, cultural systems, and the environment. Interest in production is at the forefront of much archaeological research into ceramic materials, and is also intertwined with broader matters of household and political economies, and of trade and exchange. The present chapter addresses the topic of determining the location of pottery production, which can be approached from several directions.

20.1 Physical Indicators

An important objective in artifact studies, and a critical first step in studying ancient pottery economics, production, and trade, is to determine where the objects were made. In ancient times and continuing to the present in many areas, the production of ceramic goods—household utensils, roof or floor tiles, bricks, flowerpots, tourist items—exemplifies what has been called a cottage or domestic industry (Muller 1984) or simple commodity production. The pottery recovered at an archaeological site may have been made as part of a small-scale operation in a residential patio or backyard, or on a larger scale in a workshop or compound (fig. 20.1); the workshop may be situated in a sector or *barrio* of a large city that is the site being excavated, or it may be hundreds of kilometers distant. Manufacture may take place in urban areas (see, e.g., Lynch 1979) or in rural settings tied to larger urban or regional economic networks.

In some areas of the world, identifying pottery manufacturing loci poses little difficulty: direct evidence, such as documents, and physical remains, such as firing facilities, reveal their presence. For much of the ancient world, however, this information remains hidden or ambiguous and archaeologists must rely on indirect evidence and procedures, such as spatial dispositions of tools and styles. To understand production arrangements, both direct and indirect approaches are used to integrate physical data with theories, concepts, and models pertaining to the locations of fabrication along with the associated social, economic, and political institutions and processes.

Figure 20.1 A potter's kiln shed in Ticul, Yucatán, Mexico, showing piles of wasters and stacks of saggars (*left*) in front of the kiln.

20.1.1 Artifactual Indicators

Efforts to identify specific loci of manufacture may be based on the occurrence of tools used in making pottery or concentrations of raw materials and finished pottery products (table 20.1; Kardos et al. 1985; Nicklin 1979; Stark 1985; Stark and Garraty 2004; Sullivan 2006). For example, piles of raw clay, tempering materials, or mixed clay plus temper; the presence of turning devices, wheels, molds, saggars or other kiln furniture; and the siting of kilns or other firing facilities are useful and largely unambiguous indications of past pottery manufacture. These may be supplemented by finds of pigments, and finishing and decorating tools.

The perishability of some of these indicators limits their utility in some areas. Unconsolidated clays and pigments may erode or be dispersed during the hundreds or thousands of years of post-occupational weathering or reuse of a site. Unfired vessels, especially if found in quantity, may indicate manufacturing in a given area, as they are fragile and unlikely to have been moved great distances. In north coastal Peru, unfired pots were found in elite Moche tombs, perhaps indicating hasty funerary preparations (Shimada, Häusler, Hutzelmann et al. 2003b). However, unfired pots can easily disintegrate in wet conditions. Finishing tools, such as scrapers, or objects for incising or impressing may be ad hoc tools made of pottery fragments and easily mistaken for random sherds (e.g., López Varela et al. 2002). Others are of perishable materials

(gourd rind, bamboo, cane, leaves) and survive only in exceptional circumstances. The archaeological visibility of potting households or workshops has been addressed in ethnoarchaeological studies in Chiapas, Mexico (Deal 1983: 97–111), and in Egypt (Nicholson and Patterson 1985a). Table 20.2 compares the frequency of several archaeological indicators of pottery making in potting versus non-potting households in two Chiapas communities.

Table 20.1 Data Useful for Inferring Locations (Communities, Sites, or Individual Workplaces) of Ancient Pottery Production

Proximity to high-quality clay resources
Location near modern potting communities
Presence of kilns
Presence of burned soil areas—red soil, ash deposits, thermally altered rock
Presence of kiln furniture—stilts, props, saggars
Presence of firing wasters
Presence of pottery-making tools—wheels, molds, polishing stones, etc.
Stashes of raw materials—clay, temper, mixtures of clay and temper
Quantities of unfired vessels
Quantities of identical vessels (style, shape)
High frequency of locally made vessels
High frequency of different types of vessels

Note: No single one of these criteria is necessary or sufficient to prove production locations, nor do any of them necessarily indicate anything about the organization of production.

Over much of the world, pottery manufacture was carried out without wheels or turntables, and even where these were used they were often made of perishable wood; similarly, much pottery was fired without kilns. Accumulations of wasters—misfired or overfired sherds and vessels (fig. 20.2) (see Blackman et al. 1993; Johns 1977b)—and concentrations of ash are useful evidence, because firings typically produce a relatively high percentage of damaged or unusable pieces. Wasters may be difficult to identify, however, because sherds or broken vessels may be reused in firing to prop vessels in place or to provide a temporarily insulating cover over the fire (see Stark 1985: 174–76).

Table 20.2 Comparison of Potting and Non-potting Households in Aguacatenango and Chanal, Mexico

	Potting Households	Nonpotting Households
Number of households with stored clay	25 (78%) of 32	0
Number of households with stored temper	22 (69%) of 32	X[a]
Number of households with smoothing stones	14 (42%) of 32	0
Average number of *metates* per household	2.1 (n = 28)	1.4 (n = 22)
Average number of local vessels per household	36.8 (n = 25)	26.2 (n = 24)
Average number of types of pots per household	7.1 (n = 25)	5.2 (n = 24)

Source: After Deal 1983: 97–111.

[a] Temper is occasionally present in Aguacatenango non-potting households; people collected it and exchanged it for pottery in nearby Amatenango (Deal 1983: 110).

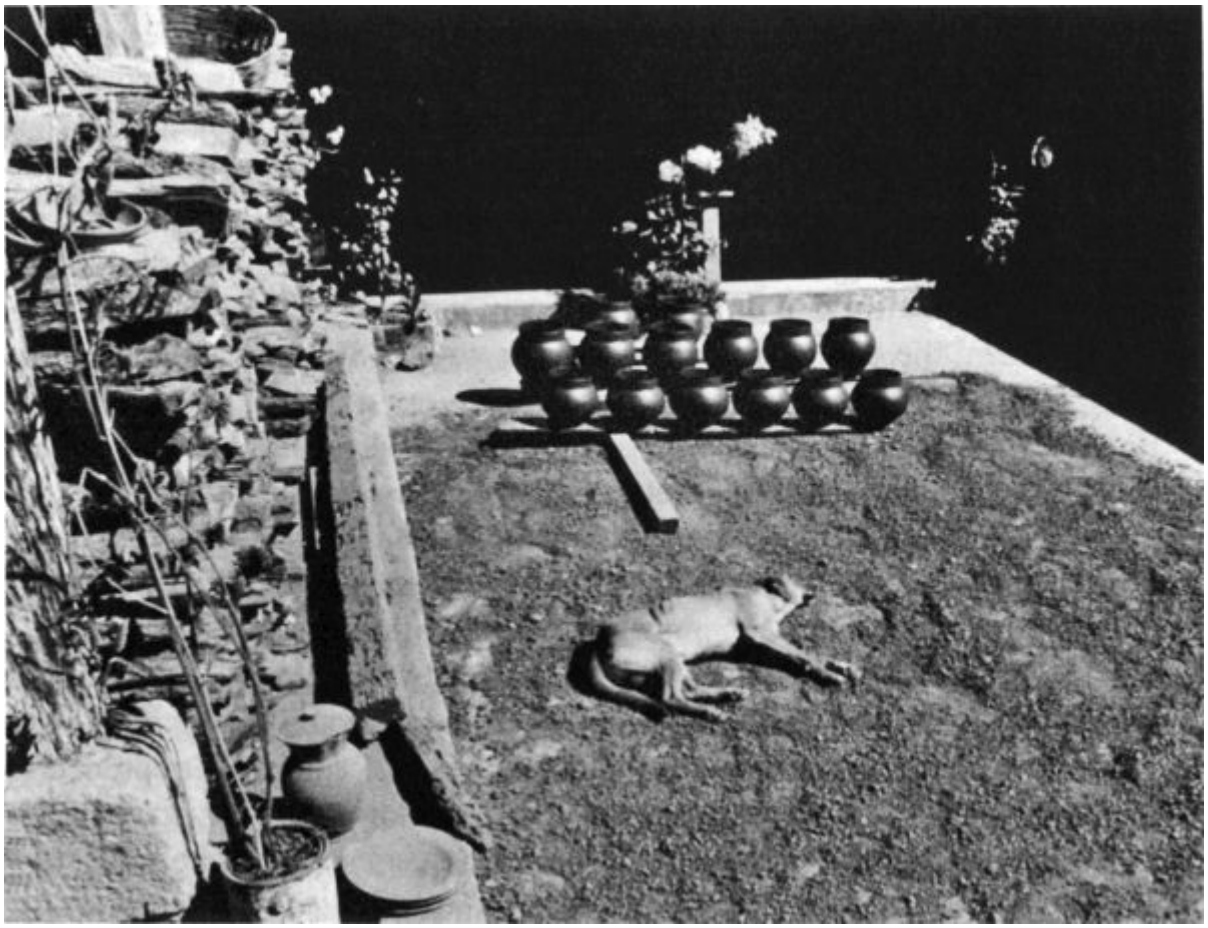

Figure 20.2 The interior courtyard of a potter's workshop in Antigua, Guatemala. Firewood is stacked to the left, freshly made pots dry in the sun in the background, and a sleeping dog sprawls on the crushed clay spread on the floor

of the patio.

20.1.2 Spatial Indicators

Various social factors may determine where potters work (e.g., Costin's [1991] "context" and "concentration" variables). The demographic and socioeconomic position of potters in a society may dictate that pottery making is limited to small numbers of producers by any number of sanctions or institutions such as age, sex, marital status, clans, or caste systems. This may be indicated architecturally if potters live in a ward- or *barrio*-like clustering of residence-cum-production loci, as at Teotihuacan, Mexico (Sullivan 2006). Modern pottery manufacturing communities are often sited in urban fringe areas, in part because the heavy smoke from firing pots, whether in open fires or in kilns, may be objectionable (Lynch 1979: 5). Thus potters' quarters, firing areas, or workshops may be on the outskirts of large sites, or downwind according to prevailing winds.

One clue to the general locations of pottery manufacture in antiquity is the spatial dispersion of ceramic styles. Known as the criterion of relative abundance (Bishop et al. 1982: 301), this principle suggests that goods were probably made where they are most abundantly found and were moved from that location by some exchange mechanism. With respect to pottery, the underlying assumption is that at most sites the bulk of the pottery was made locally. This spatial approach, which harks back to early Americanist anthropological concepts of culture areas and the "age-area hypothesis," and also gravity models from geography, has formed the basis for many archaeological reconstructions of economic relationships and chronologies.

The location of contemporary potting communities may be clues to ancient producing sites, on the premise that they tend to be situated relatively near clay resources. Several researchers have agreed with the observation that "according to least cost principles, the bulky materials used in fabricating pottery—the clay and temper—are less likely to have been obtained from a distant location in preindustrial societies than the clays or pigments used for finishing and decorating" (Rye 1981: 12; see also Arnold 1980, 1985: 32–60; Bishop et al. 1982: 315–16). A survey of procurement distances in the ethnographic literature on pottery-making revealed that potters tend to obtain their resources from a "preferred territory of exploitation" extending a relatively short distance from their working locations: 85% of 110 potting communities used clay and temper resources obtained within a radius of only 7 km, although distances may extend as much as 50 km from the manufacturing location (Arnold 1980: 149, 1985: 39–49). Other ethnographic data reveal that the location of pottery-making communities is influenced by multiple factors (e.g., Nicklin 1979: 449–51), of which proximity to resources and to markets (in the sense of consumers rather than formal marketplaces) may be most important. Neither of these can be given absolute primacy, however, and contrary cases are known from ancient and modern times (see sec. 8.1.1).

Potters' perceptions of the suitability of clays sometimes may be governed more by sociopolitical considerations and trade alliances than by the reality of the geophysical environment. Moreover, highly desirable clay resources may be exhausted by intensive manufacture, requiring that clay be brought from distant areas (e.g., Hancock 1984: 210; Arnold et al. 2000). In China, porcelain was made from the white kaolin clays in Jiangxi Province for centuries, but by the seventeenth century that source was exhausted and potters had to import clay from 60 miles away (Staehelin 1965: 38). A similar situation existed with fuel: after deforestation of the surrounding hillsides, wood for firing the kilns had to be brought from as much as 300 miles distant.

There is no simple formula to predict the presence or pinpoint the location of potting communities merely by the occurrence of high-quality clays, principles of least cost aside. Identifying the geographical site of manufacture and locating the geological sources of the clays are two distinct research objectives. Moreover, locations of firing vessels may be apart from locations of forming them.

It has also been noted that potters often occupy—whether by choice or by circumstance—land with very poor agricultural potential. This has suggested that the impetus toward pottery making at the household level—which is not infrequently associated with poverty and a need for supplemental income—may be the inadequacy of the agricultural subsistence base in these regions (see Arnold 1985: 198–99; Stark 1991: 71). This interpretation has had some opposition (e.g., Cook 1984: 20–21) and the extent to which this contemporary correlation may reach into precolonial and precapitalist times has not been satisfactorily explored.

20.2 Provenience/Provenance

The goal of many compositional analyses of pottery is to determine where it was produced, a procedure known as *provenience* analysis at least since the early 1970s, but more recently dubbed *provenance*. These terms are not strictly equivalent. Archaeologists widely agree that provenience specifies the location of recovery or findspot of an artifact. Provenance has been adopted into Americanist anthropological archaeology from European archaeology and fields such as art history and museum studies. In the latter, the term generally refers to an object's life-history: typically a documented history of ownership or custody *since* it was created, not the source of the raw materials used to create it. Few archaeologically recovered objects, even in historical archaeology, have anything approaching such a pedigree; from a behavioralist perspective, this essentially refers to re-incorporation into a new systemic context following ancient discard into archaeological context. Hence, the term provenience is used inclusively here to refer to the origin or source of an object: its archaeological findspot, its geospatial location of production, and its geological raw material sources determined instrumentally.

20.2.1 Compositional Analyses

Compositional provenience analyses seek the geographical and geological origins of artifacts on the basis of their composition. The term refers to one important objective, along with a suite of related assumptions and techniques, pursued by archaeometric or archaeological science characterization analyses since the 1960s. Since then, such studies of pottery and other artifacts have become routine in archaeology. Analyses begin with characterization of an artifact's mineral or chemical (or both) constituents and properties.

These studies are pursued under an assumption known as the "provenience postulate" (Weigand et al. 1977: 24; see also Bishop et al. 1982: 301; Rands and Bishop 1980: 19). Articulated with respect to chemical analyses, this postulate holds that

- compositional differences between distinct raw material sources or deposits can be recognized analytically; and
- as a corollary, these compositional variations will be greater between sources than within sources.

Note that, with respect to pottery, the provenience postulate does not specify any relations between a raw material, such as a clay or temper, and a finished and fired artifact made of that clay. Provenience is thus framed not as a cultural problem (e.g., as one of "provenance" sensu stricto) but as a geochemical problem. This makes it difficult to translate the findings into human decisions and behavior related to pottery production and exchange.

In the case of pottery, mineralogical identifications are most commonly carried out through petrographic analysis. In some cases, petrography alone may be sufficient to determine regions of resource procurement and hence manufacture (see Peacock 1970; Shepard 1942a, 1965), because mineral inclusions may be distinctive enough that a particular geological locale can be specified. Petrographic analysis may be most informative for differentiating local from "intrusive" pastes in the following circumstances (Shepard 1976: 165):

- Extensive exchange of stylistically similar pottery over broad regions;
- Importation of pottery in such large quantities that local manufacture seems more logical;
- Poor preservation of sherds, preventing examination of surface finish or decoration; and
- Recognition of unusual inclusions in initial sorting that suggest nonlocal manufacture.

Geochemical characterization of pottery has favored INAA and, increasingly, LA-ICP-MS and its variants. Determining the geochemical source of pottery artifacts is a complex procedure, the complexities perhaps best illustrated by contrast with obsidian (Glascock et al. 1998). Obsidian is volcanic glass of felsic composition—that is, it was formed by rapid cooling of a lava flow and its composition is primarily silica (SiO_2), which is colored black, gray, or brownish (sometimes green or red) chiefly by iron and magnesium. Worldwide, the occurrence of obsidian is limited to volcanic geological zones and as a glass it is compositionally relatively homogeneous within a flow. Once the source flows in a region are adequately characterized chemically—and this was accomplished decades ago, with databases widely shared among archaeometry laboratories—they can often be differentiated in archaeological material by a relatively few elements (and by pXRF spectrometry). The chemical composition of an artifact of obsidian is not altered from that of its source by the addition or subtraction of substances during manufacture.

Procedures are less straightforward in the provenience analysis of pottery. Pottery is a geochemically complex substance, composed of multiple kinds and amounts of particulate mineral matter. Clays occur in all habitable environments of the world and often in large deposits, which may vary compositionally from top to bottom or laterally. Potters may modify clays by adding mineral grains to fine clays or by removing them from coarser sediments. Thus, source clays and other raw materials, and the pottery made from them, are highly variable both mineralogically—unlike obsidian—and chemically. The natural variability of the source is compounded by potters' actions and choices during manufacture.

Complex multivariate statistical manipulations allow comparison of the obtained compositional data (the groupings or reference units) of pottery of unknown origin against the composition of better known or previously analyzed materials. These "knowns" may be of two kinds:

- Clays and tempers from the geological resource procurement zones in the region where the pottery of interest occurs, or

- Material from identified production locations, such as finished products or kiln wasters from a specific site or workshop.

The two bodies of chemical compositional data—from the unknown sherds and from either known resources or wasters—are then compared to determine whether the unknowns and the knowns are "the same," that is, the statistical probability that they represent samples drawn from a single (or from an identifiable number of) geological/geochemical population(s). This process relates to two additional postulates in provenience studies (Stoltman 1989: 312–17):

- The "local-products-match" postulate, which refers to comparisons between unknown vessels and vessels of known local production;
- The "spatial-pattern" postulate, which concerns the expected homogeneity of variations within sites versus heterogeneity between or among sites.

Each approach to knowns has a slightly different emphasis in terms of interpreting production. Comparisons with resources are directed not toward identifying the location of the human action of creating the artifacts, but rather toward identifying the geospatial and geological source region of the raw materials—clay, temper, pigments—and how they are used (see, e.g., Jorge et al. 2013). This approach is aligned with ceramic ecology and resource specialization in production. These data are also useful in differentiating indigenous or local from foreign or trade wares or in distinguishing imitations by means of atypical constituents.

In comparing compositional data to previously analyzed sherds or workshop materials, provenience analyses endeavor to link unknown ceramics with known manufacturing origins (a procedure close to identifying site specialization). These do not always reveal patterns of resource use within and between production units (the spatial-pattern postulate). Furthermore, the composition of pottery at a site is not necessarily constant through time if there is a very long occupation (cf. Attas, Fossey, and Yaffe 1982), because different clays may be used, clays may be exhausted, and the same clay source can vary geochemically from one part of the bed to another.

20.2.2 Confounding Factors

Confounding factors in provenience analysis can be considered from two viewpoints: the behavior involved in manufacturing a pot and the physicochemical analysis itself. Because most of the attention to these issues has focused on the latter, more data are to be found on geochemical precision than on the relation between making a pot and variations in constituents.

In the analysis of pottery, trace chemical methods are most easily and successfully applied to finer-textured materials. These methods are less suited to characterization of very coarse, sandy pastes because of their extreme inhomogeneity, and different analytical methods—INAA versus LA-ICP-MS, for example—may yield different

results (Wallis and Kamenov 2013; see also Jorge et al. 2013). Such sandy materials are better suited to initial investigation through petrography. To a certain extent the behavioral confounding problems are less severe with petrographic than chemical characterization, because these thin section analyses take into account some aspects of manufacturing and allow consideration of texture, particle size and orientation, porosity, and so forth, as well as suggesting the mineral basis for the chemical constituents of the products. On the other hand, "the compositional and petrographic groups do not necessarily coincide. Some chemical groups have a mineralogical explanation, while others do not" (Falabella et al. 2013; see also Neff 2011, 2012).

20.2.2.1 Analytic Confounding Issues

Most of the advances and developments in provenience studies of archaeological objects over the past fifty years have occurred in two areas, instrumentation and statistics. Advances in instrumentation have brought greater sensitivity and precision in element analysis, while refinements of the statistical transformations of the massive amounts of quantitative data have yielded automated mathematical techniques for grouping sherds by composition in statistically meaningful ways (but see Michelaki and Hancock 2011). These divide the overall assemblage into discrete groups that minimize variation within the groups and maximize it among groups.

Compared with obsidian proveniencing, one problem is that clays are ubiquitous, particulate sediments rather than geographically isolated, homogeneous glassy outcrops. They are variable from deposit to deposit in their chemical and mineralogical constituents, partly because many different clay minerals exist, but also because weathering, transport, and redeposit of the material can lead to complex mixing. By their very nature, clay materials lack the relative depositional and compositional integrity characteristic of obsidians.

When chemical analyses, such as XRF and INAA, first began to be applied to archaeological pottery, two critical issues were selecting the elements by which individual ceramic groups were to be differentiated and compared with known and characterized materials (clays or kiln products), and consistency among labs (Harbottle 1982). Ideal elements were good discriminators, had good analytic precision, and were reliable in terms of contamination in the postdepositional environment (on postdepositional alterations, see Golitko et al. 2012; Secco et al. 2011). Half a century of refinement of INAA has eliminated the uncertainties underlying this issue, but it is worthwhile to mention some of the considerations.

The two major chemical constituents of clays, alumina and silica, typically are not used to differentiate deposits because of overlapping concentration ranges (as well as the extremely short half-life of alumina as measured in INAA), but minor constituents such as iron, calcium, potassium, magnesium, and sodium are useful. It is generally wise to eliminate (or correct statistically for) elements that have correlated occurrences: for

example, potassium, rubidium, cesium, and barium tend to substitute for each other in K-feldspars, and calcium and strontium occur together in limestone. In terms of analytic precision, the "best-behaved" elements, with standard deviations of only 1%, were found to be iron, thorium, chromium, sodium, and potassium; almost as good, with standard deviations of 2–4%, were cobalt, barium, samarium, and manganese (Harbottle 1982: 70). The elements selected should also occur reliably in nature, but only a few studies have sampled large clay beds to determine the variation in element occurrences (e.g., Arnold et al. 2000; Neff et al. 1992).

The kinds and sources of variability in a compositional analysis can be expressed in an equation as the mathematical quantity of variance (Bishop, Harbottle, and Sayre 1982: 273; Bieber et al. 1976: 68–70; Bishop 1992: 167): $ST^2 = SN^2 + SS^2 + SA^2$

- ST^2 is the total variance in determinations of the quantities of a particular element in a sample, representing the sum of the natural, sampling, and analytic variances.
- SN^2 is the natural variance, representing the naturally occurring variation in concentration of a particular element in a material.
- SS^2 is the sampling variance, arising from errors in estimating the quantity of an element owing to problems in sampling the sherd.
- SA^2 is the analytic variance, resulting from errors in the quantitative measurements of the analysis procedure, including detection, calibration, interferences, and data processing.

SS^2 and SA^2 represent the parts of the variance that can be controlled by the analyst; SN^2 is that part inherent in the particular materials being studied. The sampling error can be made very small by careful work. A requirement that these errors introduce a contribution of 10% or less into the overall standard deviation of the results suggests a practical criterion for the analytic precision: $SA^2 \leq \frac{1}{4}SN^2$. In some cases of very homogeneous materials, the desirable level of analytic precision for provenience studies is on the order of 1–2% (Wilson 1978: 222), but in some cases precision of only 7–10% was acceptable (Harbottle 1982: 70). Instrumental and statistical refinements in analytic methods have reduced the errors of SA^2 to these desirably low levels, while larger sample sizes, repeated analyses, and careful calibration with standards reduce both SA^2 and SS^2.

To compensate for some of the many sources of variation between clays and archaeologically recovered pottery, different types of sample pretreatment may be recommended before chemical analysis (see Wilson 1978: 224–25). Some investigators soaked sherds in distilled water to leach out elements acquired from the burial environment or to bring samples to similar condition with respect to water-soluble constituents (Sayre et al. 1971: 168). Another procedure is to prefire samples at temperatures of 700°C to 1000°C, a practice sometimes recommended to eliminate the "diluting" effect of organic matter, water, and volatiles (such as SO_2 or the CO_2 from carbonates) in low-fired sherds. In all cases removing areas of surface contamination is

critical, although this does not eliminate diagenetic remineralized deposits in porous materials.

20.2.2.2 Behavioral Confounding Issues

Manufacturing a pottery vessel involves various steps that can distort the relationship between the chemistry of the original raw clay and that of the vessels made from it: SN^2 in the above equation. Despite the instrumental and statistical data-processing sophistication of most compositional and provenience analyses, "real-life" pottery-making behavior adds large amounts of variability to that naturally present within and between sources, and these can interfere with efforts to compare fired pottery with raw materials. Numerous early compositional studies treated the potential sources of variation between clays and fired ceramics (e.g., Adan-Bayewitz and Perlman 1985; Arnold et al. 1978; Bishop 1975, 1980; Bishop et al. 1982: 294–95; Brooks et al. 1974; Buko 1984; Freeth 1967; Hancock 1984; Olin and Sayre 1971: 200). These almost always, however, used different sample materials and small numbers of specimens, and thus until recent second-generation studies these issues saw little systematic exploration with suitably sized sample sets.

Of all the possible sources of variation, the most significant concerns inhomogeneities related to granulometry: variations in the kinds and sizes of particles between clays and fired pottery. Translated into potters' behavior, these variations involve either selective removal of relatively large size-grades of particulate matter (for example by sieving or levigating) or additions of such material to the original clay as temper (see Neff et al. 1988, 1989; Wallis and Kamenov 2013). Each can cause serious difficulties for provenience analyses that compare sherds with raw clays. One early solution to the size-grade problems was to analyze coarse and fine fractions of sherds separately (Fillières et al. 1984) before comparison with possible clay sources. Continuing debates on the relative contributions of different particle size fractions—clay matrix versus temper—to overall chemical composition underscore the complexity of these relations (Blackman 1992; Elam et al. 1992), which may be type- or locale-specific.

Sand-sized particles are common in clays and it was long claimed that quartz sand would simply dilute the element content of the product (Olin and Sayre 1971: 200; Sayre et al. 1971: 174), especially when present in amounts less than 25%. Similarly, where clays are marly, or calcareous materials (limestone, shell) are incorporated into the paste, Ca can dilute the composition and the data may be mathematically corrected for this (Cogswell et al. 1998). In the case of quartz, there is no such thing as "pure" quartz sands as most sand deposits, especially volcanic sands, contain varying amounts of heavy or accessory minerals that contribute trace elements. Some sands, for example in northern Florida, are high enough in heavy minerals (esp. zircon, monazite) to be mined industrially (Calver 1957: 15–25; Olsen et al. 1990: 252–53; Wallis and

Kamenov 2013: 904). If what is removed from or added to a clay is largely quartz sand, there may be little change in composition except for silicon, but if feldspars, heavy minerals, and dark-colored, heavy mafic (ferromagnesian) minerals are removed the trace-chemical composition could change considerably. Comparative analyses of quartz sand–rich Florida-Georgia sherds by INAA and LA-ICP-MS revealed much higher (mean 57%) elemental concentrations in the latter (Wallis and Kamenov 2013: 898–99, 902).

Similarly, many types of igneous and metamorphic rocks (sandstone, basalt, trachyte, etc.) that may be crushed and added to the clay as temper contain heavy minerals. Other added ingredients include calcite, limestone, and crushed sherd, and in all these examples the minor and trace elements in these materials will supplement those of the clay. Investigations of such relations generally examine clays and tempers from a single geological region, for example volcanic ash in the volcanic highlands of Mexico (Hirschman and Ferguson 2012). In the case of the Classic-period lowland Maya, however, volcanic ash was added to local clays weathered from this limestone environment.

Another problem for provenience analyses results from potters tempering one clay with another. This practice is known historically in the manufacture of Spanish (and some Mexican) majolicas, and also ethnographically, with potters using complex combinations of several clays as among the Gamo of Cameroon (Arthur 2006: 34) and the Shipibo-Conibo of Peru (DeBoer and Lathrap 1979).

Technically, even the water added to make a clay plastic can contribute elements registered in the chemical composition of the fired piece, as the water might include soluble salts (cations) of sodium, potassium, magnesium, calcium, and iron. The water and some of these components will volatilize on firing and this is probably not a problem, assuming that local water chemistry is comparable with that of soil moisture or groundwater. In areas where seawater might have been added to clays (see Rye and Duerden 1982: 61–63), however, variations in chlorine and bromine have been noted between sample clays and the fired clay products, so these elements are not reliable for sourcing.

Yet another potential cause of variations in the relation between the elemental composition of a clay and a ceramic vessel is the firing process. Although the effects of firing temperature and atmosphere on composition appear to be negligible, especially at low temperatures (Cogswell et al. 1996), at higher temperatures (over about 850°C) a variety of elements may volatilize and be lost, such as chlorine, bromine, sulfur, strontium, lead, and mercury (see Poole and Finch 1972; Rye and Duerden 1982: 64). At lower temperatures the sherds will have lost fewer elements, but they will also retain some cation exchange capability that may predispose them to adsorb elements from the burial environment (see Hedges and McLellan 1976).

21 Production II: Organization

> Yet labor is always social. . . . the controllers of social labor . . . are assigned to their positions by the system of deploying social labor, which casts them in the role of elder kinsman, chief, seignorial lord, or capitalist.
>
> Wolf 1982: 74

Ancient pottery production has been studied via varied data, methods, and viewpoints, some focusing on the producers and some on the output, some emphasizing the political and some the economic, some direct and some indirect, and often in combination. The present chapter overviews some of the concepts and models archaeologists have used in approaching pottery production. The emphasis is on identifying organizational arrangements and their interrelations with distribution.

21.1 Mode, Scale, and Intensification

The concepts of mode and scale of production are heuristics that describe the various ways surplus goods are extracted and appropriated.

21.1.1 Mode of Production

The concept of mode of production, developed by Karl Marx, denotes a "specific, historically occurring set of social relations through which labor is deployed to wrest energy from nature by means of tools, skills, organization, and knowledge" (Wolf 1982: 75). Classic modes of production in the literature include Marx's Asiatic mode (Godelier 1978 [1964]), Marshall Sahlins' domestic mode (1972; also Meillassoux's [1981] "domestic community," and lineage production); the many capitalist modes of production, plus kin-ordered and tributary modes (see Wolf 1982: 73–100). Modes of production also can be characterized as labor-intensive and capital-intensive. These can be distinguished, even in non-industrial-capitalist contexts, by manufacturing technology infrastructure, such as kilns and wheels. These devices permit rapid production of large quantities of virtually identical products (mass production), but they require substantial capital investments and dedicated space for efficiency.

With respect to pottery, mode of production generally refers to interrelated labor and organizational arrangements, such as kinds of producing units (e.g., households, workshops), roles and statuses of producers, task integration, and manufacturing technology, all of which relate to consuming groups and the overall economic structure. Distinctions between labor intensity and capital intensity in studies of archaeological pottery production may be evidenced by the kinds and distributions of pottery-making tools.

21.1.2 Scale of Production

Scale of production, with respect to pottery, refers to the levels of labor and resource inputs, including clay and temper, and the kinds and quantities of output—that is, the pottery products. More specific variables include the number and location of producing loci and their size, including spatial extent and production rate, and the kinds and quantities of manufacturing technology (workshop structures, wheels, drying space, firing facilities, etc.) (see Costin 1991: 91; Mills and Crown 2000: table 1.1; Pool 1992). The size of production units also incorporates variables such as the numbers of workers and the existence of task groups (including their recruitment, composition, and integration) that obtain and prepare resources, form vessels, finish, decorate, fire, or sell the product. These arrangements are more commonly phrased in terms of horizontal, vertical, or functional divisions of labor.

Production scale is also closely tied to distribution and demand—the numbers and locations of consumers of the pottery. The role pottery plays in communitywide ceremonies or fiestas also affects demand, and can be a major determinant of the seasonal volume and rhythms of production (e.g., D. Arnold 1999: 65; Howry 1976: 210; Lynch 1979: 5–6; Reina and Hill 1978: 249).

If specific production sites are known, information on the products might be gleaned from wasters, but scale—as measured by quantity of output—will be difficult to ascertain except by estimating the volume of individual firing loads (and frequency of firing will remain unknown absent written records). Otherwise it is necessary to extrapolate to an entire assemblage from frequencies and/or use-lives of pottery categories of interest recovered in unmixed residential middens or other deposits. Questions about the rate of production are not likely to be answered this way, however, given the generally poor level of fine chronological control at archaeological sites.

21.1.3 Intensification and Specialization

Intensification of production, whether through greater investments of labor or capital, is one way to increase output through either intensification proper or through specialization. Intensification is a key concept in theories about the development of societal complexity (e.g., Morrison 1994), and is typically discussed with reference to agricultural production. Specifics include the hypothesized causes of the intensification, such as population pressure, and intensification's correlates (e.g., declining marginal returns, accumulation of storable surpluses, labor asymmetries).

- Intensification proper raises the output per unit of land or labor, either by increasing the frequency of production events (e.g., increasing the frequency of cropping) or by increasing the yield per event (through technological investment or increased labor input).
- Specialization is a strategy of intensification that increases output through concentration on a single crop (monocropping).

Scale and mode merge with general intensification in the concept of specialized production. In some areas during antiquity, increased production of foodstuffs was accompanied by increased production—that is, quantitatively more and qualitatively more varied—of goods and services, leading to socioeconomic differentiation and societal complexity. This labor intensification and differentiation, or "division of labor," is thought to have led to the development of economic specialization (e.g., Dow 1985): an intensification strategy to increase production output by concentrating on a single product or limited number of products.

21.1.4 Mode, Scale, Intensification, and Complexity

Matters of mode and scale of production can begin to be approached intuitively in terms of general levels of societal complexity. At one extreme, in small villages weakly integrated into broader regional economies, production of basic domestic goods may be

pursued in households primarily for "own use" or informal exchange. Both input and output are relatively low; manufacture may be on a seasonal or as-needed replacement basis and demand may fluctuate according to the circumstances of individual households. Pottery making is likely nearly invisible archaeologically and resists quantitative investigation because of lack of investment in tools and facilities.

At the other extreme, large, complex, urban societies are likely to have multiple and complex arrangements for producing agricultural and nonagricultural goods as well as for distributing them. Their large, dense populations create relatively constant consumer demand, necessitating relatively continual provisioning to serve varied utilitarian and specialized needs. At this scale, archaeological signatures, such as investments in structures and technology, may be visible and often spatially segregated (fig. 21.1).

More specifically, in many areas "craft" specialization likely accompanied the emergence of elites, as part of their strategies to further their political agendas and manipulate their political authority and power (Peregrine 1991: 1; see also Schortman and Urban 2004; Sinopoli 2003). In the case of pottery, these processes might have occurred when certain producing units (households, workshops, *barrios*, communities) began to concentrate, by choice or by fiat, on manufacturing a functional, formal, or decorative category or categories of pottery that served as an elite or prestige good. Specialization in this sense might have arisen independent of other kinds of intensification.

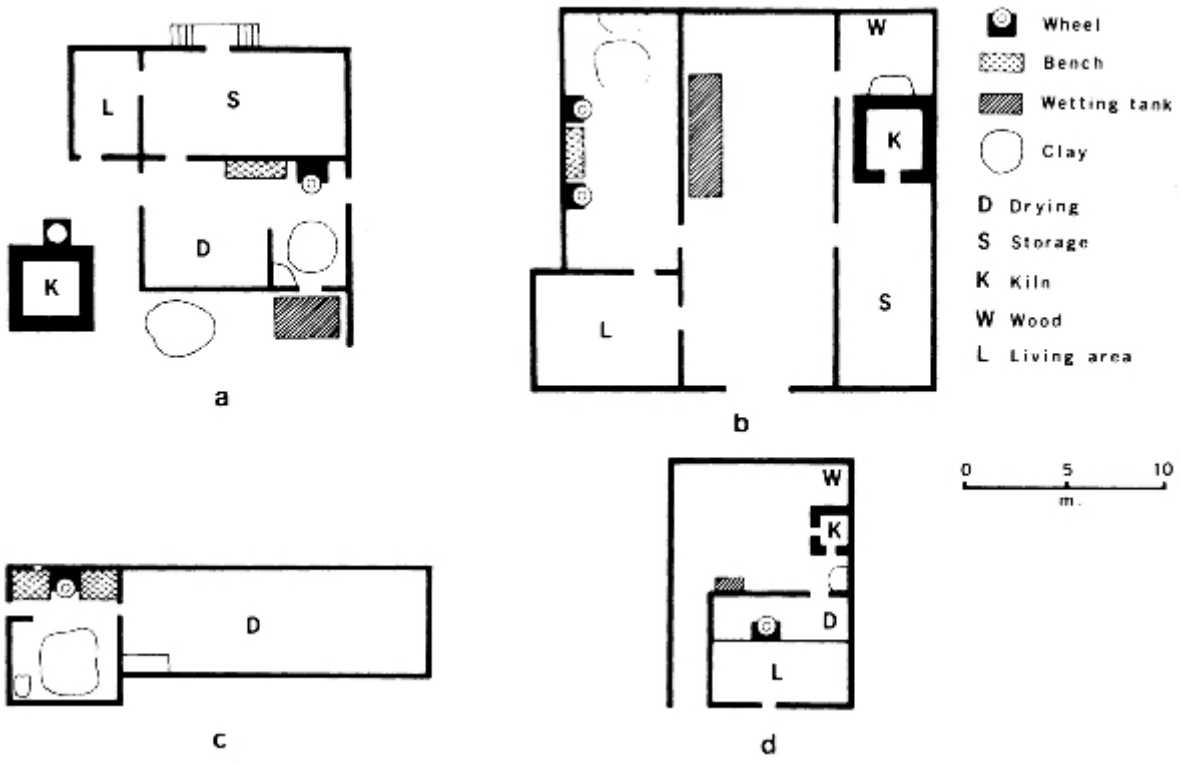

Figure 21.1 Workshop plans: *a*, Orei, Euboea, Greece; *b*, Viana do Alentejo, Portugal; *c*, Deir el-Gharbi, Egypt; *d*, Saõ Pedro do Corval, Portugal. Sources: *a*, after Peacock 1982: fig. 11–1; *b*, after Peacock 1982: fig. 11–2; *c*, after

Nicholson and Patterson 1985a: 55; *d*, after Peacock 1982: fig. 11–3.

The two examples, rural villages and urban centers, are extremes, of course, and between them is a large continuum of middle-range societies with varied economies and production arrangements.

21.2 Specialization

Archaeologists' interests in production have focused for decades on the "specialized" production of various classes of goods, hence "craft" specialization. This interest follows V. Gordon Childe's (1946, 1950, 1958) proposal of an "urban revolution" in the ancient Near East, calling attention to its highly skilled workers in the prestigious craft of metallurgy (see Wailes 1996a, 1996b). Specialist production has not been viewed with comparable fascination by ethnographers and ethnoarchaeologists, however. Ethnographers' general lack of scrutiny might be taken to suggest that specialized production could be an idealized Western construct sprung from Childe's Marxism; or, perhaps it pertains only to the contingent circumstances at the core of Childe's evolutionary model (see Patterson 2005); or, maybe it has little meaning for production in today's capitalist global marketplace with its glut of plastics. Nonetheless, anthropologists developed some minimal criteria for identifying specialization: proportion of time devoted to the activity, amount of subsistence (or income) gained, existence of a native title or name (ethnotaxonomic category), and receipt of some remuneration (Tatje and Naroll 1973).

These criteria pertain, obviously, to the producers themselves and their labor. They clarify the sometimes vexing question of just what is "special" in specialization: the producer, the process, or the product? Ethnographically, it is the producer. However, these criteria are not easily transferred to, or operationalized in, archaeological contexts, although archaeologists have endeavored to do so, particularly invoking the time commitment criterion. But except in situations, largely urban, in which the scale and mode of production clearly point to substantial investments in facilities (capital intensification) and a large consumer base, archaeologists have had to infer specialization from proxy indicators: primarily the ceramic product (chap. 22).

The differences in observables between the ethnographic present and the archaeological record meant that for archaeologists, the first methodological and theoretical issue was to determine whether any form of economic differentiation and specialization existed in a particular situation. Economic or occupational specialization carries multiple senses or meanings and can include ritual specialists, for example, but archaeologists are particularly interested in production of goods. Specialization can be conceptualized as encompassing several strategies of labor intensification and skills differentiation leading toward increased production output. If specialized/intensified production did exist, when and why and how did it develop? How can this concept be operationalized in research?

Archaeologists try to build hypothetical scenarios or models about what the organizational arrangements of the producers might have been if specialized production existed: *if* this pottery were produced by specialists, *then* we would expect the pottery to exhibit [insert characteristics] and/or to find [insert traits] at a site or region. It is in

these issues of pottery production, particularly the preoccupation with "craft specialization," that the disjunctions—or, perhaps better said, the limitations of analogies—between ethnography/ethnoarchaeology and archaeology are strikingly apparent.

21.2.1 Types and Models of Specialized Production

Archaeologists have few widely applicable models for understanding arrangements of pottery production in the past. Ideally, such models should illuminate the behavior and decisions involved in scale of production, mode of production, variability in products, and, of course—given the longitudinal perspective of archaeology—changes, both long and short term, in any of these. One also would be able to identify the location of the activity. Most of the time, however, some or all of this information is unavailable.

Several schemes have attempted to organize the many dimensions of pottery production arrangements into idealized, quasi-evolutionary typologies (Clark and Parry 1990; Costin 1991, 1996, 2001; Peacock 1981, 1982: 8–10; Pool 1992; van der Leeuw 1977, 1984). These generally posit categories of specialization based in part on data and analogies drawn from ethnographic and historical records. Early schemes distinguished production arrangements primarily by location, household vs. workshop, then further differentiated them by sex, technology investment, and consumership.

For interpreting production in antiquity, such schemes raised several problems (see Clark 1995; Costin 2001; Patterson 2005; Smith 2004: 82–83). Modes are tied to societal evolutionary stages. Time commitments and scheduling cannot be known. Household or domestic modes are likely to leave little trace archaeologically because of lack of material technological investment. Descriptions of production incorporate statements on distribution. Females are passive, their agency limited to households and minimal or ad hoc technology, while males have active agency in workshops with technological investments in wheels and kilns. Different production arrangements may exist for different categories of pottery: so-called prestige wares—with high value, special function, low consumption, or restricted distribution—may participate in spheres of economic activity in different ways than utilitarian wares (with low value, high consumption, and wide circulation).

A particular obstacle in these schemes is a lack of middle-range comparables. Over the past century of modernization and globalization, along with the encroachment of plastics, pottery production has become more and more restricted to "women's work" in the household in underdeveloped countries (the "feminization of labor"). Male potters produce in workshops, today and in the past, but their analogs in antiquity come through historical and archaeological studies of civilizations: for example, the Roman estate and military systems (Peacock 1982: 10–11), Chinese imperial porcelain "factories" (Shangraw 1977; Staehelin 1965), and the extensive arrangements for

producing majolica and shipping containers around sixteenth-century Seville (Lister and Lister 1987).

The issue is not a need for precise present-day analogs of all ancient behavior and institutions, but rather a concern over how to combine a multitude of variables in ways that illuminate productive arrangements and transformations in different situations of social, political, and economic complexity. Subsequent iterations of long-standing quasi-evolutionary typologies decoupled individual variables from the aggregate production types (e.g., Costin 1991, 1999, 2001; Pool 1992), allowing their roles to be analyzed separately and from the viewpoints of both theory and ethnoarchaeology. These variables of production arrangements include some of the following:

- Frequency/scheduling of production (year-round, seasonal);
- Intensity of production (per unit time);
- Remuneration;
- Skill level;
- Number of workers;
- Age, sex, status, and kin relations of workers;
- Degree of labor or task division;
- Technology investment;
- Kinds and quantities of output;
- Uniformity (standardness) of output;
- Kind and extent of investment in special space or tools (e.g., dedicated workshops, kilns, levigation tanks);
- Producers' location, numbers, and spatial proximity; and
- Consumers' location, numbers, and spatial proximity.

This listing itemizes thirteen dimensions or variables of production arrangements; additional dimensions might include the kinds of resources acquired and processed (clays, tempers, pigments, glaze ingredients, fuels) and modes of decoration (something akin to the "production step measure"; Feinman et al. 1981). Depending on how these variables are coded or incorporated into an analysis, there might be 15–20 or more attribute states to consider. Minimally, this is 15 factorial (15!) or 1,307,674,368,000 possible combinations of pottery production variables of interest. Clearly it would be impossible—indeed, undesirable—to try to incorporate all of these, even if hierarchized, into a study of pottery production in antiquity.

Because one important aspect of scale, the scheduling and time commitment of producers, is impossible to determine in most archaeological situations, the scale aspect of specialization might be operationalized in terms of the ratio of producers to the numbers of consumers (Dietler and Herbich 1989: 160). Although this presumes considerable knowledge of the location and size of both producing and consuming groups, it is of interest because it draws attention to processes of both intensification (Habicht-Mauche 2000) and commoditization (Dietler and Herbich 1989: 160).

Alternatively, it has been suggested that, instead of trying to include all these variables, some of them—skill, standardization, scale, and intensity—should be moved out of reconstructions of production arrangements in situations where production is

"segmented" (D. Arnold 1999: 79–80). This term refers to complex production arrangements in which the tasks within an individual workshop are themselves specialized, with master potters, apprentices, painters, kiln setters, and so on.

21.2.1.1 Producer Specialization

Most archaeological discussions envision "producer" specialization: pottery production as an economic concentration of an individual or of groups. Producer specialization refers to a politico-economic strategy of labor allocation toward surplus production in a particular economic activity, a strategy entailing increased labor input and diversification of skills. The goal may be quantitatively or qualitatively increased output. But by which of these variables can producer specialization be operationally defined and interrogated in the archaeological record? The producer's labor commitment: full-time or part-time? Degree of economic dependence on production? Skill level or expertise? Volume of output? A single product, such as a water jar? How does the task or process specialization of painters—of Greek vases, Italian majolicas, Chinese porcelains, Maya polychromes—or of kiln loaders and stokers articulate with more general levels of specialization? Generally, producer specialization does not refer to common divisions of labor by sex, for example men digging clay or making large, heavy wares while women make smaller dishes.

One approach to this complex issue distinguishes specialists, or individuals having an occupational (or task, or process) specialty or special skill, from the existence of economic specialization in the context of the "self-sustenance" of a domestic unit (group or community). That is, "Having a *speciality* does not, in this context, imply *specialisation*, that is the exclusive practice by an autonomous productive unit, of a non food-producing activity that implies continuous transfer of subsistence goods to the specialized unit. Practising a *speciality* does not necessarily imply relinquishing agricultural work" (Meillassoux 1981: 37).

This distinction removes one of the thorniest criteria in discussions of production in antiquity: defining producer specialization by full- versus part-time commitment. But even full-time specialization has two connotations:

- A sole pursuit to the exclusion of other gainful activities, versus
- A year-round economic pursuit or livelihood.

These are blurry distinctions even ethnographically and virtually invisible in the archaeological record. Moreover, the seasonal aspect of many economic activities in agrarian societies raises questions about whether this difference is meaningful at all. Potters may concentrate their potting, particularly their firing, during the most favorable weather (e.g., the warm or dry season) and continue to produce but at a different *rate*—only sporadically or with reduced output—during cold or rainy periods. In addition,

potters may also have landholdings and work their farms during the agricultural season, making pottery at other times.

An example comes from the famed porcelain center of Jingdezhen, China. In 1905 manufacture (i.e., firing) was highly seasonal, because most of the 104 workshops and kilns in the town employed summer help: "During this busy season, when every kiln is perhaps employing an average of 100 to 200 men, the population of Ching-tê Chên [Jingdezhen] rises to about 400,000, but of this nearly, if not quite, half are labourers drawn from a wide area of country . . . who only come for the season, live in rows of barracks-like sheds, and do not bring their families with them" (W. J. Clennell, quoted in Hobson 1976: 155).

Full-time producers—those who make pottery at a relatively constant rate year-round and do not produce food—may be found only in state-level societies (Muller 1984: 493), primarily in or near urban areas with sizable and dense populations to establish continuous demand for virtually all goods. In smaller, nonstratified societies, such a degree of producer specialization may be risky during times of economic stress or famine if there are no political provisions for redistribution (Hayden and Cannon 1984: 341).

Another focus of theorizing producer specialization distinguishes two kinds of specialists on the basis of the consumers of the goods, as attached versus independent (Brumfiel and Earle 1987: 5; Earle 1981: 230).

- Attached specialists typically produce ritually or functionally specialized products—wealth or prestige goods—for elite patrons as part of their control and manipulation of the political economy (see also Peregrine 1991). Attached metallurgical specialists producing for political elites in the Near East were the foundation for Childe's ideas about craft specialization (Wailes 1996b).
- Independent specialists, by contrast, produce a range of products for general consumers. They operate largely without specific directives or intervention other than local preferences and needs, although taxation or tribute demands may impact scale. These producers likely manufacture commodities—goods having both use and exchange value—but their specializations are variable.

This distinction can be identified in many complex societies, and has been particularly well investigated among the Inkas and Aztecs. It does not appear to be evidenced in others, however, including the Northwest Coast, where elites themselves are specialists (Ames 1995), and also Hawai'i (Lass 1998). Similar questions can be raised about such attached arrangements among the Classic Maya, where the painters of court and mythological scenes on polychrome vases are thought to have been elites (Rice 2009: 140).

21.2.1.2 Community Specialization

Sometimes producers of pottery congregate in a single community, often part of a regional system in which each of multiple communities produces a different kind of good for exchange. In highland Mexico and Guatemala, for example, different communities produce pottery, baskets, grinding stones, and leather goods, exchanging

these products within a bounded “solar marketing system” (see Nash 1966; Smith 1974: 176–77). Similar community-based specializations exist in Ghana, where villages restrict themselves to manufacture of particular wares or forms: pots for palm wine at one, spindle whorls at another, and utility wares at a third (Crossland and Posnansky 1978: 88). Comparable situations are found in the southern Peruvian Andes (Tschopik 1950: 215), in Melanesia (Ellen and Glover 1974; Lauer 1970), in Oaxaca (Feinman and Nicholas 2007), and among the Kalinga and in many other areas (Neupert 2000; Stark 1991). In highland Mesoamerica, production may be by men or women and is usually part-time and seasonal (table 21.1). Community specialization does not necessarily imply producer specialization, and determining time investments and other considerations is a separate issue.

Table 21.1 Characteristics of Pottery Making in Two Highland Mexican Towns

	Household Production (Chanal)	Village Industry (Amatenango)
Frequency	Occasional/part-time	Part-/full-time
Organization	Work separately	Assembly line within extended family or guild
Market	Home use; intracommunity	Local or regional
Seasonality	Dry season	Year-round
Division of labor	None	Considerable
Manufacturing technology	Hand, small tools	Hand, small tools
Firing technology	Open fire	Open fire
Time per vessel	<20 minutes	>30 minutes
Raw materials		
Clay	Black and red; local (<1 km)	Black, white, yellow; local (<1 km)
Temper	Calcite; distant (2–8 km)	Calcite; local three types of sand; local
Fuel	Pine kindling, oak bark; local	Pine kindling, oak bark, cypress; distant (>5 km)
Pigments	Not used	Distant (purchased)
Smoothing stones	Local	Distant (8–60 km)
Investments	Time only	Cash for pigments and transportation
Range of functional types	Narrow	Wide
Range of wares	Unslipped only	Slipped (red and white) and unslipped
Role of men[a]	None	Gather firewood, help with firing, help with marketing

Source: After Deal 1983: table 17.

[a] Women are the potters in both communities.

Site or community specialization (in producing any good) may arise in certain localities with fortuitous environmental factors such as good fishing, fertile soils, mineral deposits, and so forth (Muller 1984: 490–93, 1987: 15). Or it may arise because of their absence: In the Pasil River valley, there is "an inverse relationship between the amount of farmland and the degree of specialization in each Dalupa household. Specialist potters live in households with inadequate access to land, and these potters ply their wares at a sufficiently large scale to fulfill household needs. Clearly, community-based specialization in the Pasil area reflects ecological and non-

ecological factors" (Stark 1991: 71; see also D. Arnold 1978, 1993 for the Valley of Guatemala and highland Peru, respectively).

21.2.1.3 Resource Specialization

A related specialization focusing on select raw resource materials for commodity manufacture might be called "resource specialization." A striking example comes from sixteenth-century Italy, where INAA of *maiolica* produced in six centers revealed that, although the forms and painting styles differed, the calcareous paste compositions were statistically indistinguishable (Myers 1992). The reason for this homogeneity was unclear, however. It might have resulted from transport of clays from a single source to the six producing centers, from transport of bisque-fired vessels produced at a single center to other centers for painting, or from a single clay source with an extremely wide natural distribution (Myers 1992: 153–54). Nonetheless, resource specialization seems clear (Bishop 1992: 170).

Another example is the production of glaze paint pottery in the Rio Grande area of New Mexico, made possible by the availability and control of an essential material (lead ores for the paint) as well as superior clays for the body and slip, and which led to specialized production of the ware as a trade commodity (Creamer 2000; Habicht-Mauche et al. 2002; Thibodeau et al. 2013). Similarly, in Tanzania, highly refractory local clays are a valuable resource for traditional specialized iron-workers, who use this material to build their large furnaces and *tuyères* (Childs 1988, 1989, 1990).

Distinguishing resource specialization from other categories of specialist production could be important for interpreting the results of pottery provenience analyses. Provenience analyses model pottery production in terms of a geological or geochemical data set that, by principles of least cost and ethnographic analogy (plus the provenience postulate and the criterion of abundance), should represent a zone that is hypothetically or actually relatively near one or more distinguishable clay or temper sources (or other distinctive raw materials) (see, e.g., Tite 2008). Although identifying the specific clay beds exploited to make specific kinds of pottery may well be an unattainable objective for many studies, ideally some correspondences should be sought between the geochemical groupings and human behavior. This would mean that the groupings might represent patterns of choosing and using resources within individual producer units. As one example, INAA of clay and pottery from three workshops in Ticul, Yucatán, Mexico, revealed that the workshops could not be distinguished (Arnold et al. 2000). Instead, given that the tested clay sources were only 3 km or less from each other—and thus probably represented a single geological deposit—the analyses supported more general conclusions about compositional analyses reflecting communities of potters and also communities of practice.

In early applications of physicochemical analyses to archaeological pottery, socioeconomic questions relative to production—the behavioral, decision-making,

organizational, and social-structural components of anthropological interest—seemed to be viewed as epiphenomenal. Provenience was, as noted, a geochemical issue, not a cultural one. Thus it is important to incorporate data on variability in cultural attributes of pottery, such as form, decoration, and thickness, in interpreting compositional data in the study of pottery provenience, as in the epigraph to chapter 20. Computerized clustering programs are available for analyzing mixed-level (combined quantitative chemical and qualitative cultural) data, and these are useful in refining provenience interpretations away from the solely geochemical (Philip and Ottaway 1983; Rice and Saffer 1982; Wishart 1999, 2006).

21.2.1.4 Product Specialization

Given the limitations of the archaeological record, and in the absence of satisfactory concepts and models spanning the gap between theory and data, it would seem that the study of pottery production would logically seek to operationalize key concepts through the product (see chap. 22) rather than the elusive producer. Thus the idea of "product" specialization might be useful. As mentioned, so-called attached specialists frequently concentrate on certain products, such as wealth or prestige goods, for a limited set of consumers, whereas independent specialists produced general commodities. Community specialization arrangements may often develop around a specific product, which might relate to their proximity to distinctive resources.

Metallurgy in Shang China has been described as including product and process specializations or technologies, differentiated by organizational factors (Franklin 1999: 13–19; Li 2007: 203). In prescriptive technologies, workers execute specific tasks—such as throwing, painting, or glazing in the case of pottery—and they may have little knowledge of all the steps of creating a finished pot: this describes process specialization (or task specialization), which has come to dominate the world today in industrial mass production. Holistic technologies, by contrast, are organized so that one person understands and performs the entire series of procedures, or what might be called product specialization.

21.2.2 Multicrafting

Another matter of considerable interest skirts the singularity aspects of producer (or other) specializations and instead concerns itself with the relations between pottery production and production of other goods. For example, are there similar kinds or degrees of specialization in making chipped lithics as in making pottery? The concept of "multicrafting" describes what may be a widespread practice.

Multicraft production refers to "the concurrent practice of multiple crafts by different individuals or groups, each specialized in one or more crafts, in the same space or in a series of adjacent spaces" (Shimada 2007b: 5). Among the Classic Maya, several closely arranged elite residences at the site of Aguateca yielded evidence of production

of various goods. Residents of one structure in particular appear to have done scribal and/or painting work and made pyrite mirrors, as well as using clay for some undefined purpose (Inomata 2007; Inomata et al. 2002). Others were engaged in various combinations of bone-working and carving, along with scribal work. In seventeenth-century Yucatán, multicrafting was common, as a Spaniard remarked that "What causes wonder is that there are many Indians who work at four or six trades where a Spaniard would have but one" (López de Cogolludo 1974: 15). Papers in a recent edited volume (Shimada 2007a) describe multicrafting in several New and Old World sites, suggesting that the practice might have been far more common in ancient times than is currently recognized.

* * *

Michael Smith (2004: 82) recently suggested that the term specialization has "outlived its usefulness . . . and should be abandoned." I suggest, instead, that specialization retains some usefulness if set in broader contexts and given greater specificity, and that it is the concept of "craft" specialization that needs to be rethought, if not abandoned. The term might be considered semi-redundant, given that at least one discussion of crafting refers to "specialized skills that . . . are imbued *by definition* with qualities of asthetics" (Helms 1993: 6, emphasis in original). At the same time, in its everyday usage crafting often refers to a pastime or hobby that carries "undertones of regressive ruralism," with "housewives . . . lovingly painting wooden geese, cows, or pigs in . . . milk paint colors" (Shanks and McGuire 1996: 76). The term craft production serves at least partly to distinguish the creation of material goods from agricultural goods, but with modern industrialization the terms craft and craftsman have lost earlier connotations of advanced skills, apprenticeship, and professionalism. In referring to a key contributor to the material wealth of preindustrial societies, then, the term "crafting" lacks a certain gravitas, and the producers and products are better referred to in terms of artisans, artisanship, and artisanry or goods.

22 Production III: The Products

> The compositional data provided more precise information on the natural variation of the raw materials; the petrography provided a better way of detecting culturally differentiated recipes for manufacturing pottery.
>
> Falabella et al. 2013: 49

Archaeologists are frequently forced to reason backwards—that is, retrodictively and indirectly—in inferring mode of production and specialization from characteristics of the output, such as exceptional skill, standard dimensions, rare resources, and so on. The notion of product specialization calls attention to the role of studying the pottery products themselves for insights not just about location of manufacture but also about the social and economic organization of production. Organizational arrangements may be oriented toward production of only certain products, whether as a consequence of local resources or local needs, and this focus provides several avenues for studying production.

Thus one approach to understanding pottery production in antiquity begins with analyzing variability in the material produced through different production modes, using comparative data from archaeology and ethnography. Such variability in attributes of archaeological pottery is typically ordered into time-sensitive units such as types, but it is not unreasonable to envision that certain aspects might be directed toward production-based interpretations. Quantitative or qualitative differences in attribute states could be systematized to capture behavioral dimensions interpretable in terms of the kinds of specializations discussed in chapter 21. A related product-oriented approach to production, less common but particularly important to economic history, concerns commodification and the processes by which ceramic goods came to be produced primarily for exchange.

22.1 Attribute Variability and Specialization

Archaeologists have often pursued questions of pottery production arrangements indirectly, through patterns of attribute variability in the products as proxies for organizational features. Production can be considered a process of variety generation, whereas consumption is variety selection; together these create cultural patterns distinctive of different socioeconomic arrangements (Redman 1978: 173). The underlying premise is that pottery attributes encode information on variables of production strategies (including technological decisions in manufacture) much as decoration can be considered a code. Thus formal or dimensional variability should—in principle—vary with productive mode. In household production, form variation, for example, may be high (table 22.1).

Table 22.1 Olla Form Variants Produced in Potting Households in Chanal, Mexico

Household ID number	Spheroid	Ellipsoid	Pointed Ovaloid	Round Ovaloid	Cylindrical	Hyperboloid
3		x	x			
4	x		x			
6		x				
7[a]	x		x	x		
9		x	x			
10		x				
13	x	x	x	x	x	
14[a]		x	x			
15[b]	x	x		x	x	
16		x				
17				x		x
19		x				
20		x	x			
22		x		x		
24		x				
25[a]		x	x	x	x	
27		x				
28		x	x	x		
29	x	x				
30		x				
31[a]		x	x	x	x	
37		x	x	x		
41				x		
43	x	x		x		
45[a]	x	x	x		x	
48[b]	x	x	x	x		

53		x		x		
Totals ($N = 27$ households)	8	23	13	13	5	1

Source: After Hayden and Cannon 1984: table 8.

[a] Two potters in household.

[b] Three potters in household.

Specialized production typically has been conceived to entail fewer workers society-wide who are individually more skilled ("specialists") and who, in aggregate, produce more vessels for a larger corpus of consumers, with greater efficiency, under conditions of reduced time and labor investments. Whether through prescriptive or holistic organization principles, this is accomplished through routinized manufacture, characterized by diminished variability both in resources and in the processing, forming, finishing, and firing operations that require fine motor skills acquired through experience. This routinization occurs in response to considerations analogous to modern industrial production concerns with cost-effectiveness and quality control.

For archaeologists, these labor considerations should, in principle, be recognizable in reduced ranges of variability in form, dimensions, and other attributes of the pottery. This expectation has been operationalized through the concepts of standardization and diversity, two heuristics that, although not directly addressing scale and mode of production, represent quantifiable approaches to these production variables encoded in sherds.

22.1.1 Standardization

Standardization was originally conceived as a process of reduction in variability as pottery making became an increasingly restricted or focused occupation (i.e., "specialized") through time (Rice 1981, 1991a; Toll 1981; see also Balfet 1965: 170; Shepard 1958: 452). This reduction in variability can be conceptualized in other ways, such as increased homogeneity or uniformity of the products. One expectation of this process is that, given a situation of increasing specialization, compositional and technological attributes would vary less as the range of behaviors surrounding resource procurement and preparation, and also firing procedures, is limited or regularized. Another is that attributes of form will vary less (i.e., be more standard) if molds or other devices are used for forming and shaping, or if production involves other similarly restricted ranges of physical movements and techniques. Considerations of quality control, efficiency, and cost-effectiveness are expected to be important, not necessarily framed as in today's monetized economy but in terms of resource and labor inputs compared with outputs.

The concept of standardization has implications for the production, distribution, and use of pottery in archaeological contexts:

- With respect to manufacturing and production, standardization implies an increasingly limited range of materials and more formalized or routinized techniques (mass production, molds), resulting in virtually identical products (see Peacock 1982: 121–22, citing Goudineau 1968 for Arretine Samian pottery; Rottländer 1967, 1968). Standardization, as a proxy for specialization, is thus also a proxy for scale (and mode) of production (i.e., intensification).
- With respect to distribution, standardization may be evident over time in increased production of uniformly sized vessels that stack or nest well for transport (fig. 22.1; cf. D. Arnold 1999: 75) or suggest standard units of measure.
- With respect to consumption and use, the standardization of sizes and quality of vessels will likely affect their functions, demand, and rates of replacement and entry into the archaeological record.

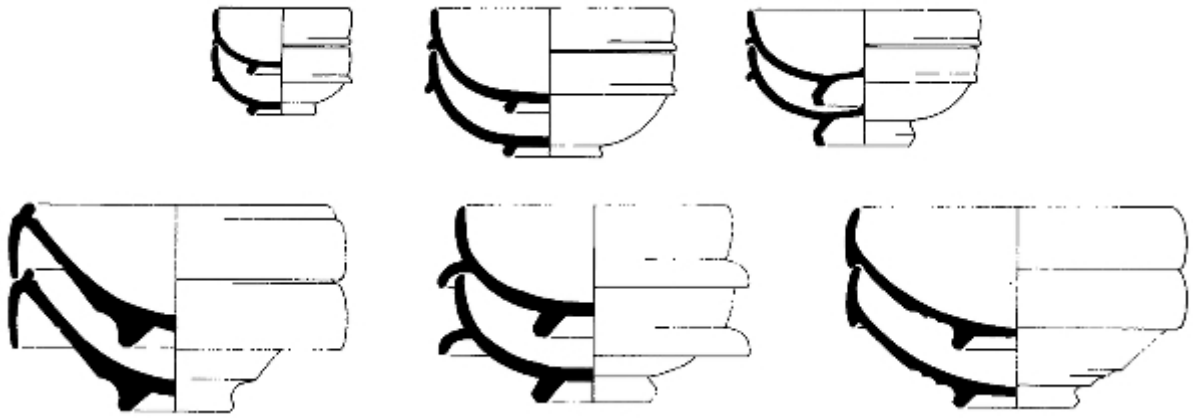

Figure 22.1 Stacking of Roman provincial bowls, aided by flanges and ridges on the outside. After Rottländer 1968: fig. 7.

Numerous studies have investigated standardization and the "standardization hypothesis" with archaeological and ethnoarchaeological data, yielding inconsistent findings (e.g., D. Arnold 2000; Arnold and Nieves 1992; P. Arnold 1991; Benco 1988; Berg 2004; Blackman et al. 1993; Kvamme et al. 1996; London 1991b; Longacre 1999; Longacre et al. 1988; Rice 1991a, 1996: 176–82; Roux 2003; Stark 1995). Part of the problem is that standard*ization* was proposed as a process occurring over time (see, e.g., Dal Sasso et al. 2014), but it is difficult to measure with static snapshot samples: time is no longer the independent variable. These studies addressed the variables used (primarily dimensions) and the size of the sample, and the degree to which a given collection of pots exhibited standard*ness* (i.e., uniformity or homogeneity) on some attribute(s). An important general concern here is validity: Are these attributes the best measures of the property they purport to measure? Are standardness or standardization valid indicators of developing productive specialization? Do cross-cultural comparative studies of attribute variability mean anything useful with respect to production organization?

Whether variations in dimensions or other attributes are statistically (and behaviorally) significant is a related but different question. This has been assessed via an *F* test or calculation of a coefficient of variation (CV) (Eerkens and Bettinger 2001). One study specifically explored the relations between skill and metric uniformity using

the dimensions of the products of four potters in each of three potting communities in the Philippines. The CVs in the three communities ranged from 3–4% to 12%, the lowest (indicating greatest uniformity) supporting the hypothesis that greater experience and skill of the potters in this community result in more standard products (Longacre 1999). Similarly, a cross-cultural investigation of variation in dimensional attributes with intensity of ceramic production (i.e., scale; rate of output) found greater standardness (less variability) associated with high rates of production (Roux 2003).

Relatively little investigation has been directed toward standardness of nonmetric attributes of pottery, such as composition—an index of resource specialization. These have been based primarily on INAA analyses (see Stoltman 2001: 318–19 for petrography). Dean Arnold's comparison of paste composition over 30+ years in several pottery-making communities reflected changes in resources but concluded that, with respect to the question of what composition "can tell us about the organization of ceramic production," the answer is "not much" (2000: 369). But the examples were drawn from household-level production, rather than different levels of intensity of production. Interesting insights come from INAA analyses of early Nazca pottery in coastal Peru, which revealed compositional variability in plainwares, whereas polychrome painted vessels formed a single compositional group (Vaughn and Neff 2000). The plainwares were likely products of household production, and the polychromes were probably brought into the site by some form of exchange with a non-local manufacturing center.

Analysis of jugs in a fire-destroyed Middle Bronze Age workshop on Cyprus suggested that standardness was focused on vessel shape, as opposed to capacity (Frankel and Webb 2014). Fine-ware bowl wasters from the third-millennium BC site of Tell Leilan, Syria, provided the basis for an unusually thorough analysis of three indices of standardness (Blackman et al. 1993). Samples from a fused stack of wasters were chemically more homogeneous than even the NIST standard reference (Blackman et al. 1993: 69), but other fine wares representing the products of multiple workshops over the 200–300-year history of these vessels were more variable. In both cases, however, the CVs "for most elements are well under 10 percent," thus supporting the hypothesis of greater uniformity in workshop (or "specialist")-produced wares (Blackman et al. 1993: 77). Issues of spatial and chronological control may blur this relationship, however.

22.1.2 Diversity

Related efforts addressed the concept of diversity. Diversity was borrowed into archaeology from population ecology, where it describes the structure of an ecological community through the categorization of its constituents, such as species (e.g., MacArthur 1965; Pielou 1974). A statistical measure akin to "variance," ecological diversity indices have two components: richness, the number of categories present, and

evenness, the distribution of entities within the categories. Ecologists long disagreed on the interpretation of diversity measures, at least one of which was borrowed from information theory, although the general view is that ecologically more complex communities exhibit greater diversity.

In archaeology, diversity measures refer to variability in the numbers and sizes of categories of various kinds of artifacts in an assemblage. In the case of pottery, this might refer to taxonomic units, technological classes, form classes, or decorative styles. Richness (number of categories) and evenness (peakedness of a distribution curve) statistics provide a basis for comparisons of these categories: household-to-household, site-to-site, area-to-area, period-to-period, upper-to-lower status, and so forth. High richness and high evenness suggest access to varied resources and/or numerous producers, whereas low richness and low evenness suggest limited access to resources, fewer producers, and/or mass production (Deal 1983: 269–309; Leonard and Jones 1989; Rice 1981: 222, 1989, 1991a).

As in other situations of interdisciplinary borrowing of concepts and statistics (see Aldenderfer 1998), there are dangers of misapplication in anthropological and archaeological studies. Problems include sample size (cf. Plog and Hegmon 1993) and assessing whether differences in indices are statistically and behaviorally significant (Cowgill 1989; Dunnell 1989). Following these critiques, diversity measures largely ceased to be used in archaeology (cf. Hegmon 1995 in style analysis) and their potential for ceramic studies was never realized.

However, the concept and measures of diversity are of interest to, and continue to be explored in, numerous disciplines such as science and technology policy (Stirling 2006, 2007). As one example, the properties of diversity have been reconceptualized from two (richness and evenness) into three, each of which "constitutes the other two" (Stirling 2007: 709). These new properties are variety (number of categories), balance (N in each category; variance), and disparity (roughly differences between the categories themselves; distance). Rather than a single index of diversity that theoretically accommodates all variability in all contexts, it might be better to envision "a general diversity heuristic" calculated from disparities (Stirling 2007: 711–12). Similarly, in certain contexts—if one is working with a small, censused pottery collection or a nonrandom sample—Brillouin diversity may be used as a comparator (Hegmon 1995: tables 8.6–8.12; but cf. Heip et al. 1998: 75). Thus the concept of diversity might eventually be brought back to, and used more appropriately with, archaeological data, including assessments of production-related variability in pottery (see Cochrane 2003).

22.2 Commodities and Commodification

Two conjoined political-economic concepts are particularly useful for understanding intensified or specialized production of pottery (and many other categories of material culture): commodities and commodification.

- A commodity is variably described as "any thing intended for exchange" (Appadurai 1986a: 9), "any good that can be exchanged for other goods" (Stone et al. 2000: 9), and "a socially desirable thing with a use-value and an exchange-value" (Gregory 1982: 10; Hart 1982: 40–41).
- Commodification or commoditization refers to a set of interrelated and, to some extent, co-occurring processes by which goods are transformed into commodities.

Commodification and commoditization, often taken as synonyms, are slightly differentiated in one analysis: the former is "a somewhat Marxist idea, referring to the way that market values can replace other social values," whereas the latter has a slightly different sense in today's business community (Rushkoff 2005). Commoditization in business and marketing denotes the development of "a competitive environment in which product differentiation is difficult, customer loyalty and brand values are low" and, to consumers, products are largely undifferentiated except for price (Weil 1996: 1; also Hart 1982; Reimann et al. 2010; Rushkoff 2005).

22.2.1 Commodification

The processes of commodification entail an increase in output (i.e., intensification) beyond the needs of the manufacturer and his/her immediate family or residential unit and socially mandated gift-giving exchanges. This is usually a result of, or a response to, increased demand, which in turn accompanies not only population growth but also societal differentiation: social, economic, and political diversification. In other words, population growth and differentiation produce a large body of consumers who constitute a "market" for products that meet their diverse needs relating to statuses, roles, institutions, activities, and so forth.

Archaeology provides a unique opportunity to examine the processes of commodification of various goods in various settings. Commodification has implications for intensification of production (scale, specialization) and the standardization of value. It is theorized that, as small, more or less egalitarian societies began to grow and develop more complex organization, increasingly centralized socio-politico-economic ranking and power would have created a demand for prestige goods to satisfy growing needs for visible materializations of those statuses. Such goods would have been commodities in the simplest sense of being made for users other than the producer; however, they were not intended for "exchange" in the ordinary sense of the word. Commoditization marks a distinction between prestige goods or inalienable wealth, which are materializations of power and do not freely circulate (Weiner 1985), as compared with the kinds of utilitarian goods that are exchangeable. The exchange of

wealth goods is not a simple movement of commodities but rather represents a "physical embodiment" of the relations between humans and objects.

In defining a commodity simply as a good produced for exchange, it is easy to overlook some of the implications of the existence of commodities in an economy. One implication is that the goods are explicitly made for users other than the manufacturer; as a corollary, the goods are produced in quantities beyond those necessary for own-use. These circumstances reflect profound changes in the valuation of the good, both as individual objects and as a general category: the product has become alienable from its producers.

In some narrow views, commodities exist only in monetized, capitalist economies. Other, broader construals emphasize that commodities can be found in "precapitalist economies, are culturally defined and molded, and are embedded in political and social systems which they both reflect and help to shape" (Stone et al. 2000: 9; also Rothman 2000: 165–66). But because commodities are produced for exchange, they can also be considered in some senses as socially *dis*embedded and thus "can be compared and exchanged without reference to the social matrix in which they were produced" (Wolf 1982: 310–11). The ultimate expression of commodification is mass production, indelibly associated with capitalism and globalization (Haugerud et al. 2000). But mass production can and did occur in non–industrial-capitalist contexts, and goods—including pottery—were mass produced for exchange millennia before the Industrial Revolution (e.g., Poblome et al. 2002). Commodity flows in noncapitalist societies are determined more by political power and wealth mobilization strategies than by economic institutions (Earle 2002: 96–98).

How did a good such as pottery, particularly utilitarian wares, become a commodity? An understanding of how pottery was commodified would be useful for understanding ancient economies and especially production arrangements. Was pottery a commodity in a particular society? If so, when in that society's economic history did it become a commodity? What kinds of pottery were commodified? What were the circumstances of "commodity candidacy" or entry into "commodityhood," in Appadurai's (1986a: 13) terms?

The relative spatial dispersion of classes of pottery might be considered an indicator of degree of commodification. In the American Southwest, for example, a study of Río Grande glaze-painted pottery proposed that the increased scale of production and spatial distribution of this ware during a time of societal transformations and increasing complexity in the fourteenth century indicates its commodification (Habicht-Mauche 2000). Similarly, the large trench kilns near Mesa Verde suggest a greater scale of firing—probably by collaborating groups of potters—than needed for household consumption. These may represent production for exchange (Bernardini 2000) and thus a stage in the process of commodification. A better understanding of the production and circulation of non-prestige or staple goods, including true commodities such as

utilitarian pottery, is needed for a fuller understanding of pre- and noncapitalist economies.

Intensification, specialization, differentiation, and commoditization are useful concepts for analyzing processes of, and changes in, pottery production through time. They are particularly useful for the study of production in archaeological contexts because they pertain to both labor and output, but also allow these matters to be analytically decoupled. The difficult task continues to be translating these concepts into the material terms of the archaeological record. Although studies of pottery production in archaeology must begin, empirically, with physical remains (of location and output), the underlying theoretical beginnings must be fleshed out with concepts that can be operationalized—that is, identified and measured—by observations on artifacts as simple as potsherds.

22.2.2 Commodities and Trade

For a long time, the distribution sphere of pottery economics received considerably more archaeological study than did production. This is no doubt because archaeologists traditionally devoted a good deal of attention to trade and exchange in general as a prime mover in models of sociopolitical evolution (e.g., Hirth 1996; Oka and Kusimba 2008). Most of the work on exchange has been with long-distance trade and involved primarily a single good. That good is usually an item that can be easily traced to a particular source or source region, such as obsidian, jade and other semiprecious stones, certain kinds of fauna or animal products, soapstone (chlorite, talc), or metals. Highly distinctive decorative styles of pottery and their movements are also traditional foci of provenience studies. Less common are studies of the distribution of locally produced coarse pottery or other non-elite goods within the region surrounding the locus of manufacture (fig. 11.1; see Arnold 1981; Brisbane 1981; Hodder 1974c; Loughlin 1977).

Several problems need to be resolved to optimize studies of the economic processes and behaviors of pottery distribution in antiquity. Such investigations should ideally begin with an understanding of where the pottery was moved *from*—that is, its production location. Simply describing the coordinates of spatial occurrence and recovery of pottery or any other commodity is not equivalent to understanding the processes or mechanisms by which it was distributed.

Assuming that the sources of manufacture have been identified, exchange processes are often modeled by graphing the frequency of occurrence of the artifact as a function of distance from the source. Such fall-off or decay models (see fig. 22.2) graph a decline in interaction (distribution) as effective distance from the source of supply increases (the so-called friction effect of distance). Studies of the shapes of these curves have led to several useful observations:

- Different exchange processes—such as reciprocity and redistribution (sec. 11.1.1)—may produce similar spatial dispositions of artifacts, with identical curves (Hodder and Orton 1976).
- Different kinds of items have differently shaped curves (Hodder 1974b: 179–82; Orton 2000).
- Goods with high value and less bulk have greater areal distributions and hence flatter curves (their frequency declines more slowly with distance).
- Bulky, low-value goods, such as utilitarian pottery, typically exhibit high frequencies near their source and a sharp fall-off with distance beyond what may represent a day's journey; this curve represents "supply-zone behavior" (Renfrew et al. 1968: 327).
- Differences between curves, such as those of high- and low-value goods, may be a function of mode of transport (fig. 22.3).
- A curve with a "plateau and kink" structure may illustrate the exchange of items within and across boundaries (Hodder 1980: 152).
- The gradient of a curve will vary with demographic characteristics (Hodder 1974b: 173).
- The fall-off is less sharp in urban areas than in rural areas, and in larger centers than in smaller ones.

Note that if these studies are based on numbers of sherds, rather than on estimates of the number of whole vessels, inferences will vary with the differential breakage rates of the pottery, confounding estimates of exchange intensity and centralization. Proper pottery quantification (sec. 15.1) is important in reconstructing these processes.

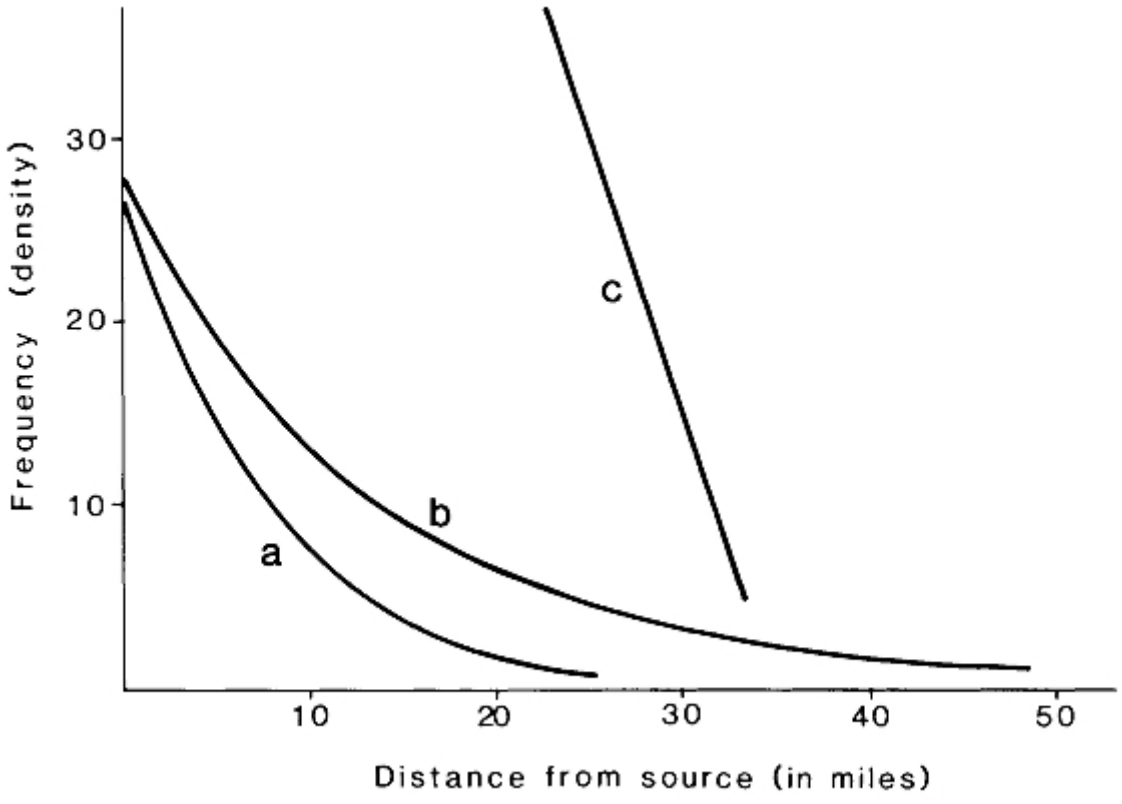

Figure 22.2 "Fall-off curves" for Savernake pottery, showing frequency of occurrence (density) of the ware as a function of distance from the production center: *a*, density or frequency of sites bearing Savernake pottery in zones around the production center; *b*, Savernake pottery as a percentage of all pottery at sites around the center; *c*, percentage of all sites in each zone possessing Savernake pottery. The steep gradient of all three curves is commonly found in fall-off curves for the distribution of coarse, bulky objects. After Orton 1980: fig. 4.9.

Apart from knowing the location of manufacture of a good such as pottery, questions of distribution are closely related to scale and mode of production, specifically with reference to how much is produced and the distance between producers and consumers. The distance a given good can be expected to move in exchange transactions is strongly affected by its transportability (Renfrew 1977: 77). Transportability is a ratio of the value of the item to its weight and to the breakage rate in transit. Most utilitarian pottery vessels have comparatively low transportability, although scores might be enhanced if transport also took advantage of their function as containers: the contents would increase their value. (Modern pottery produced for tourists, which is miniaturized and nonutilitarian, is outside the realm of these observations.) The role of mode and scale of production is underscored by comparing urban versus rural contexts. Potters producing in urban areas generally produce a greater variety of wares that travel greater distances, as compared with rural producers (Peacock 1982: 99). Rural areas may specialize in large bulk containers for storing and distributing agricultural products (Riley 1981: 136). Access to transportation, such as roads or waterways, is a related consideration.

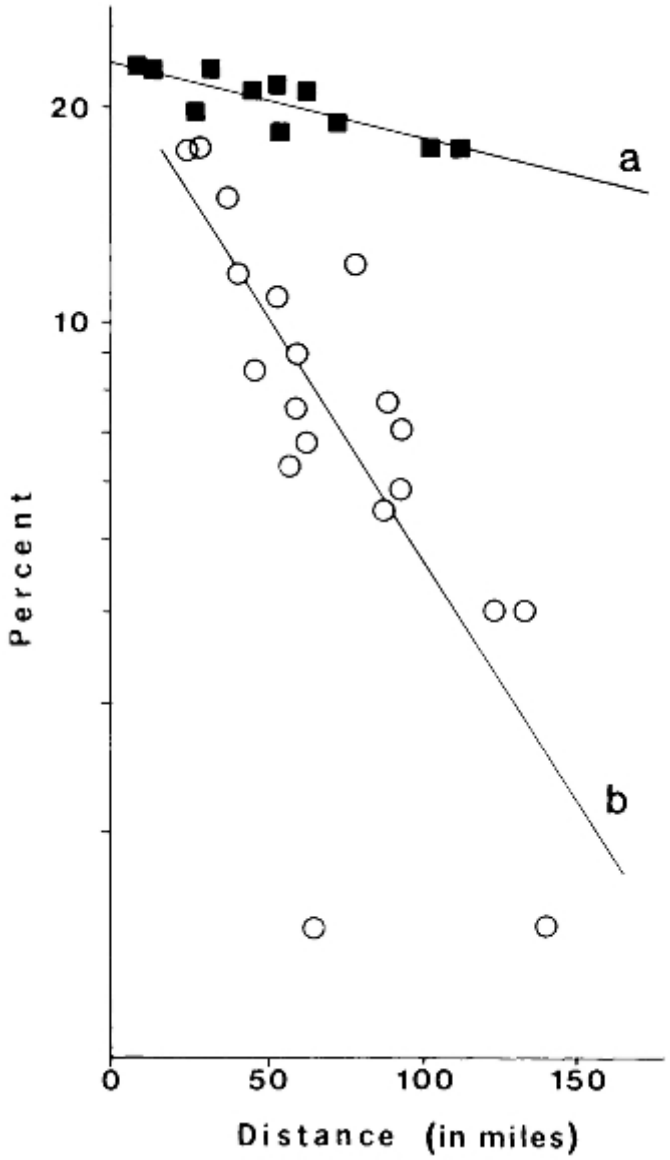

Figure 22.3 "Fall-off curves" for Oxfordshire color-coated pottery, showing percentage of the ware as a function of distance from the production source: *a*, sites obtaining pottery by water transport, indicating a slow rate of fall-off; *b*, sites obtaining pottery by overland transport, showing a rapid decline in frequency with distance. After Orton 1980: fig. 4.11.

Certain exceptionally strong or highly valued ceramic items may act as prestige goods. Such goods tend to travel farther and have a more gentle gradient in their fall-off curves in part because a restricted number of people can have or afford the item, and in part because the items may be exchangeable only for a restricted class of items that are also scarce or prestige goods (Renfrew 1977: 76–77).

Social and demographic factors provide additional complexities that argue against simple relationships between levels of exchange and distance. Where pottery manufacture is purely a household replacement activity, trade plays little role in spatial disposition, as among the Fulani (David and Hennig 1972: 21) and the Shipibo-Conibo (DeBoer 1984: 354). Migration may be a complicating factor in attempting to assess the

presence and level of trade from distributional data alone. In societies with relatively unstable membership—for example, women (potters) moving in and out on the basis of marriage exogamy or other relationships—it may be difficult to distinguish traded vessels from locally manufactured vessels of nonlocal styles.

Three interrelated points are important here with respect to the study of pottery production and exchange in ancient complex societies. One: If commodities are goods produced for exchange, and if exchange is "one of the ways value is created" (Morphy and Perkins 2006: 10), then we need to know more about exchange. "More about," here, means not just the mechanisms and pathways of their exchange and relations with distance, but also changes in these relations with time. Two: Does the increased volume of production for exchange necessarily imply some kind of specialization (Schortman and Urban 2004: 187)? And three follows from two: Does specialization imply (or necessitate) commoditization, or vice versa? Or are they independent variables?

22.3 Final Observations

Surprisingly little ethnographic research has addressed pottery economics (cf. Papousek 1981)—and if it did, it would of necessity be contextualized in postcolonial, capitalist- and global-system-oriented terms. Consequently, it is difficult to formulate congruencies between the archaeological and the ethnographic records. Enough has been accomplished, however, to require some cautions in applying the observations and models outlined above:

- Much of the information available on contemporary pottery economics concerns the relation between potters and modern nontraditional market economies, such as those tied into international tourism. Care must be taken in using these data as analogies to prehistoric situations, particularly for areas distant from urban centers.
- The full range of any society's production, distribution, and consumption relations cannot be reliably characterized by a single product, so those described for pottery do not necessarily hold true for other sectors and goods in the economy. And vice versa.
- The models of production and distribution described in chapters 20–22 are heuristic categories. In "real life" in the ancient world, the arrangements may have differed from community to community or potter to potter; any given area might have exhibited multiple arrangements, with workshop and household production side by side and consumers traveling to some potters while other potters marketed their wares through middlemen.
- The tendency to confuse place with process must be avoided. This is sometimes evident, for example, in a failure to distinguish between market and marketplace, site specialization and producer specialization, and spatial distribution (occurrence) and distributional mechanisms of exchange.
- Much economic activity is informal and difficult to model, such as various kinds of redistribution or household production. Such behavior, if not invisible archaeologically, is, at minimum, hard to isolate and verify.

These constraints make the study of pottery production, specifically, a tenuous proposition. The absence of abundant workshop evidence in many areas and a dearth of middle-range theory to bridge the gap between ethnography and archaeology render this situation all the more challenging. The total picture of pottery economics is largely conditioned by the scale of production, and many variables of scale are invisible in the archaeological record. Thus, although the presence of pottery in an area indicates that pottery production, or distribution, or both were carried out somewhere (often relatively nearby), understanding the organization (mode) and scale of those activities often depends on an indirect proxy strategy of studying the ceramic products—or, more accurately, fragments of the products—rather than directly examining the producing units themselves.

23 Archaeothermometry

Turn, turn, my wheel! What is begun
At daybreak must at dark be done,
To-morrow will be another day;
To-morrow the hot furnace flame
Will search the heart and try the frame
And stamp with honor or with shame
These vessels made of clay.

H. W. Longfellow, *Keramos*

A frequent objective in studying ancient pottery is to determine the temperature at which it was fired, a procedure known as archaeothermometry. The use-related properties of a ceramic are conditioned by three parameters of firing—time, temperature, and atmosphere—and their combined effects on the composition or phases of that object. Nonetheless, the single attribute of temperature, sometimes called the initial firing temperature or equivalent firing temperature (Roberts 1963; Tite 1969), has been accorded considerable significance.

23.1 Physical Properties

The principle underlying most archaeothermometric procedures is that after a clay has been heated in firing and then cooled, the physical and chemical transformations of its constituents will be halted or frozen at the point of maximum heating. These changes can be identified and measured in a sample of pottery as an estimate of the original firing temperature. Or, the temperature at which they stopped can be identified by reheating the sample to higher temperatures in a lab under controlled conditions, and noting the temperature at which the changes resume. In practice, multiple techniques are often combined to give a fuller picture of firing conditions.

The temperatures attained by the firing strategies of traditional potters today can be measured in several ways, including optical pyrometers, pyrometric cones, or thermoelectric pyrometers (thermocouples). For consistency in comparative studies, the technique used should be consistent because the measured temperatures of open firings may vary by technique (e.g., Nicklin 1981a).

With respect to archaeological pottery, varied methods have been applied to the problem, ranging from simple to complex observations of physical, mineralogical, and chemical properties. Some procedures are destructive, requiring that the sherd(s) of interest be broken into fragments for refiring and analytical comparisons, and most strategies benefit from—and may require—unfired clays for comparison.

23.2 Mineralogical and Chemical Analyses

Multiple methods of mineralogical and chemical analyses can be applied to archaeothermometric questions, and frequently a combination of techniques is used to check or substantiate findings.

Visual inspection can be informative if carbonate minerals are present in the pottery. If a ware is tempered with calcite or uncalcined shell and is fired to approximately 700–750°C or above, the $CaCO_3$ will dissociate, which can cause spalling (lime popping) of the surfaces after cooling, as the remaining particles of CaO rehydrate from normal atmospheric humidity. With firing temperatures of 900–1000°C or higher, however, the CaO reacts with other constituents and does not cause popping. If the surfaces of calcite-tempered vessels show conical spalls with white specks at their centers (see Vitelli 1984: figs. 1 and 2), it can be inferred that the firing temperature was between 750°C and 900°C (see Magetti 1982: 128).

Modern methods of chemical analysis are primarily spectroscopic or spectrometric techniques (see chap. 17). That is, unknowns are identified by characteristic "spectra" of the wavelengths of the emitted or absorbed radiation determined by their crystal lattice structure. In the case of archaeological pottery these chemical properties are also of interest because they aid in identification of minerals.

23.2.1 Microscopy

Microscopic methods most useful in archaeothermometry are petrography and the scanning electron microscope, particularly in providing evidence of vitrification.

With respect to optical petrography, it might be expected that, in low-fired pottery, the **α-β** quartz inversion at about 573°C would leave minute cracks because of the slight expansion of the mineral. Anna Shepard (1936: 424–25), however, reported that in all the sherds she examined petrographically she never saw any changes in the pots or in the quartz itself that would correlate with this transformation. This is partly because the change in the quartz is reversible, but also because at temperatures around 575–600°C the fabric is still highly porous and experiencing variable expansion and shrinkage as the clay minerals dehydrate.

Box 23.1 Refiring Experiments

The simplest procedures for estimating original firing conditions are based on changes in the physical properties of color and porosity. These properties can be measured by refiring sherd fragments to various temperatures in a laboratory under controlled conditions (rate of temperature increase, atmosphere, soaking period, etc.).

If a sherd can be sacrificed for destructive analysis, it can be broken into several fragments and each one refired in an appropriate atmosphere in an electric kiln at a sequence of increasing temperatures. The widest possible range likely to span the original firing temperature is desirable—for example, using 50° or 100° increments from 400°C to 1000°C or above (see Hammond 1971: 15–16). This procedure is also useful with clay resources or clay-temper mixtures. The percentage of weight lost on refiring can be useful, especially by comparison with local clays (Matson 1971). Changes in hardness are deemed of limited value (cf. Fabre and Perinet 1973).

Refiring experiments can also be used to estimate the original firing temperatures of glazed wares: small fragments of the glaze are heated and the temperature is noted when they soften and melt into a bead.

Color Changes

To use color changes to estimate original firing temperature, the color of the original sherd is measured and compared with the refired sequence. If, for example, little to no color change is noted in fragments refired at 700°C or less, but marked changes occur in those refired to 800°C and above, then it is likely that the sherds were originally fired between 700°C and 800°C. Changes in value (grayness) of the refired color may permit inferences about the general atmosphere (oxidizing or non-oxidizing) of original firing.

In heavily carbonaceous clays, color changes may not take place until after the organic matter has burned out, which may require a relatively long duration and/or high temperature of firing, especially if the clay is fine-textured. In such cases it will be very difficult to accurately interpret the refiring data as distinguishing among the original temperature of firing, the atmosphere of firing, and its duration. The utility of refiring tests can be enhanced if local clays have been collected and fired in a temperature sequence, for the resultant data then form a background or standard for comparison of color development of refired sherds as a function of firing temperature (as well as time and atmosphere) (Beck 2006a). Refiring tests are probably not particularly useful at temperatures below 500°C (and perhaps not below 700°C), because at or below these temperatures the color changes are likely to be largely a function of organic content.

Porosity Changes

Apparent porosity has some utility for estimating firing temperature, again by comparing the original value with that obtained on refired sherd fragments. As a clay begins to sinter and vitrify during firing at elevated temperatures, its pores begin to shrink, and apparent porosity decreases with increasing temperature of firing. The original apparent porosity of the sherd is measured, fragments are refired, and after cooling the apparent porosity is re-measured on the fragments. The lowest temperature that marks a change in porosity, that is, the point at which the percentage of moisture absorbed begins to decrease, exceeds that at which the sherd was probably fired.

Porosity measurements will not provide useful estimates of firing temperature on extremely low-fired sherds (below 500–600°C), because changes in porosity may be affected by postdepositional leaching and rehydration of clay minerals, and also by granulometry (Courtois 1976; Magetti 1982: 126, 129; Plant 1970). The method is most appropriate for relatively high-fired wares, those fired at 900°C or more; under some conditions it may be useful as low as 800°C.

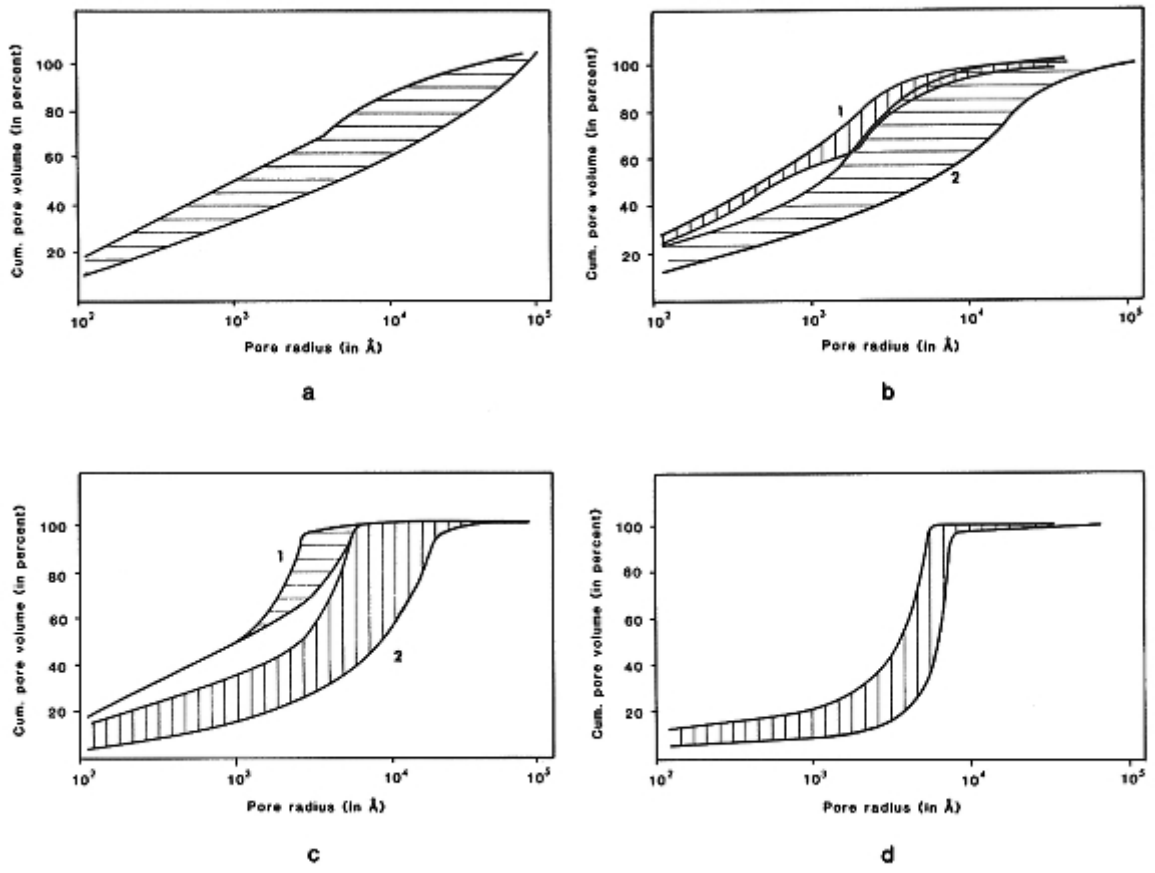

Figure 23.1 Pore-size distribution of pottery with different initial firing temperatures: *a*, coarse Dacian sherds, 500–600°C; *b*, coarse pottery, approximately 700°C (*b*1, Romanian and Assyrian; *b*2, Dacian); *c*, fine pottery, about 900°C (*c*1, Celtic; *c*2, Hellenistic, Roman, and Dacian); *d*, fine Roman and Dacian pottery, above 900°C. After Morariu et al. 1977: figs. 1–4.

Porosimetry—changes in the average pore size and the homogeneity or distribution of sizes as viewed in thin section—can provide information on firing. Distributions of pore sizes are roughly correlated with firing time/temperature characteristics, typically revealing that higher and longer firing results in smaller average pore size and a more homogeneous pore structure with a narrower size distribution (fig. 23.1). Thus porosity data graphed against refiring temperature or against the rate of rise of firing temperature provide a basis for inferring original firing temperature (Magetti 1982; Morariu et al. 1977; Plant 1970; Sanders 1973).

Another point of observation is the anisotropy or isotropy of the clay matrix. An anisotropic matrix is nonvitrified and retains its optical properties (chiefly birefringence), suggesting firing temperatures below the vitrification point. Changes in the properties of the micas—chlorite, muscovite, and biotite—also have been used as a basis for estimating firing temperature (Sabine 1958, cited in Williams 1983: 305; Shepard 1936: 427). Similarly, the transformation from green to brown hornblende at approximately 750°C can suggest whether the original firing was above or below this temperature (McGovern 1986: 35).

The scanning electron microscope (SEM) has been used to examine the microstructure of a fired piece (Tite 1991), especially the extent of vitrification and pore structure, and compare these features on sherds and refired specimens. It is not necessary to know beforehand the chemical or mineralogical composition of the sherds being tested, nor is it necessary to have local clays for comparison. An SEM investigation of Near Eastern pottery manufactured from calcareous clays showed that the collection could be divided into four groups differentiated by firing temperature ranges estimated by the degree of vitrification (Tite and Maniatis 1975a). There is some question about the effectiveness of this procedure at certain temperature ranges. Below 800°C there is little precision, because vitrification has not begun, and in calcareous clays there is little variability in extent of vitrification between 850°C and 1050°C (Tite et al. 1982: 112). Because fragments of the sherds are refired for analysis, this method can be supplemented by other observations such as color and especially porosity, which also is affected by vitrification.

23.2.2 Thermal Methods

Early efforts to determine firing temperatures of ancient pottery were based on thermal behavior, principally physical changes, when clay minerals are heated under laboratory conditions (Roberts 1963). Differential thermal (DT) analysis, thermogravimetric (TG) analysis, and thermal expansion analysis are all closely related and, whereas earlier the techniques had to be performed separately, current instrumentation is capable of combined analyses such as TG-DTG (derivative thermogravimetry) (Paama et al. 2000) and differential scanning calorimetry (Giordana et al. 2004).

Considered separately, differential thermal analysis, or DTA, measures changes in the temperature of a pottery sample while it is being heated to approximately 1000°C. These changes are measured against the temperature of a standard, an inert or non–thermally reactive substance such as aluminum oxide (Al_2O_3) that is heated at the same time and assumes the temperature of the furnace. The temperature differentials between the clay and the standard reflect reactions and changes within the clay (such as the conversion to metakaolin or mullite in kaolinite). Some reactions are exothermic (heat is given off); examples are the combustion of organic matter and the formation of high-temperature minerals, such as spinel at 900–950°C. Others, such as the loss of interlayer and lattice water, and the formation of metakaolin just under 600°C, are endothermic (heat is absorbed).

Temperature differences are recorded as a series of peaks from an arbitrary baseline (see, e.g., figs. 6.3, 6.5; also Grim and Rowland 1942; Johnson et al. 1982). Positive (upward) peaks indicate higher temperatures in the pottery than in the standard and register exothermic reactions; negative (downward) peaks mark lower temperatures in the pottery than in the standard and denote endothermic reactions. The distance from the baseline indicates the intensity of the reaction. The changes that occurred in the clay

mineral during the original firing will leave no record of peaks on experimental reheating, and thus significant temperature differentials between sample and standard begin when the original firing temperature is exceeded.

Thermogravimetric analysis (TGA) is similar to DTA in measuring changes in a clay during controlled reheating, but in this case the changes recorded are in weight. The important change accompanies the dehydroxylation of the clay and loss of chemically combined water, typically in the range of 500–700°C. A change in the sample weight, indicating water loss in that temperature range, means the sherds were not originally fired to a temperature high enough to dehydrate them completely, and the original firing temperature was below 500–700°C.

In thermal expansion analysis, the variable recorded is the clay or sherd's expansion and shrinkage during heating under controlled conditions (figs. 6.3, 6.4). This heating erases any changes that might have taken place in the sherd during deposition. The sherd exhibits the normal linear thermal expansion as the temperature rises and then begins to expand more rapidly up to about 573°C because of the alpha-beta quartz inversion (assuming the presence of quartz). At higher temperatures expansion ceases and shrinkage begins. This shrinkage temperature (T_a) signifies the beginning of sintering, and at this point the laboratory refiring has exceeded the temperature of the original firing.

If shrinkage begins at a temperature immediately higher than the 573°C quartz inversion, the vessel probably was not originally fired at a temperature high enough to start vitrification, and thus thermal expansion can reveal only that the firing temperature was less than 700°C. Thermal expansion analysis is therefore useful only for relatively high-temperature firings (>800°C), in which the beginning of shrinkage signals the resumption of the sintering process as the original firing temperature is exceeded. Experiments with thermal expansion analysis on ancient pottery have yielded estimates of firing temperatures with accuracies of ±20–30°C (Tite 1969: 141; see also Roberts 1963; Heimann 1982).

23.2.3 X-Ray Diffraction

Determination of ancient firing temperatures by X-ray diffraction (XRD; see sec. 17.1.2) is based on changes that take place in clays upon heating, as dehydroxylation progressively changes the crystalline structure and the spacing of the atomic arrangements or lattices (planes) in the clays and minerals formed from the clays. The temperatures at which these changes occur differ among the clay minerals. If the specific clay mineral composition of a particular piece of pottery is known, the temperature of firing can be determined by identifying the thermally induced crystalline transformations that have taken place as an indication of firing temperatures met or exceeded.

XRD can be used to assess both low- and high-temperature firing, but it is not very satisfactory at intermediate temperatures of 500–900°C. At low firing temperatures—below 500°C when the clay still retains part or most of its lattice structure—the method is relatively straightforward; it identifies the clay mineral(s) present and the thermally induced changes that have taken place, so one can infer firing temperature. Firing temperatures above 900°C can be estimated either by identifying (through petrography or XRD) high-temperature minerals such as mullite or cristobalite that recrystallize from the clay, or by noting other mineral phases that form at known high temperatures (Bimson 1969; Magetti 1982; Périnet 1960).

Between approximately 500°C and 800/900°C, however, the crystal lattice of clay minerals is generally lost and the resultant amorphous material will not usually diffract X-rays, so the technique may be of dubious utility for archaeothermometric purposes. Although kaolinite is generally useless for estimating firing temperature between 600°C and 1000°C, illite clays are informative between 500°C and 950°C, and in calcareous clays the formation of calcium silicates in the range of 850–900°C provides another clue to ancient firing temperatures.

Alternatively, other non-clay components can be analyzed by XRD. For example, the firing temperature of bone-decorated Bell beaker pottery in third-millennium BC southwestern Spain was estimated by XRD of the transformation of the hydroxyapatite in the bone (Odriozola and Martínez-Blanes 2007).

Ideally, XRD measurements are made while the sample is at a high temperature, but because most of the reactions studied are irreversible, an ambient experiment following heating to a given temperature may be satisfactory. In situations where the particles are too small or too poorly crystalline for XRD analysis, electron diffraction may be used instead—for example, to study metakaolin.

23.2.4 Mössbauer Spectroscopy

One method of chemical analysis used in estimating firing temperatures of ancient pottery is Mössbauer spectroscopy, which is especially useful for analyzing changes in the Fe_2O_3/FeO ratio of iron with firing. To estimate the firing temperature of prehistoric pottery, the Mössbauer spectra obtained for sherds must be compared with spectra measured on local clays likely to have been used in manufacture of the pottery. Mössbauer spectroscopy provides relatively fine temperature discriminations (Maniatis et al.1982; see also Bouchez et al. 1974; Shimada, Goldstein, et al. 2003; Shimada, Häusler, Hutzelmann, et al. 2003c; Shimada, Häusler, Jakob et al. 2003d), especially at or above 900°C.

23.2.5 Magnetic Properties

Some newer methods of estimating original maximum firing temperatures are based on the magnetic properties of the chemical constituents of a ceramic at the atomic level.

These techniques make use of the magnetic properties of the electrons in the atoms of the elements of constituent minerals (see, e.g., Kittel 1996; Spaldin 2010). Electrons are electrically charged particles that have an intrinsic spin as they orbit the nucleus. They tend to occur in pairs with opposite spins, but some electrons are unpaired. Analytical techniques based on magnetic properties apply a strong external magnetic field to a sample, and analyze the behavior of the electrons in response to a beam of energy focused on it. All materials respond to a magnetic field but some are more responsive —"susceptible"—than others. Magnetic or magnetic-susceptible minerals likely to be found in pottery are primarily mafics: not surprisingly, magnetite is highest, but others include hematite and ilmenite, with olivine, pyroxene, amphibole, and the micas lower on this property.

There are several different kinds of magnetism, of which two are of interest with respect to pottery: ferromagnetism and paramagnetism. Ferromagnetism, also known as permanent or spontaneous magnetism, is the inherent magnetic property at ambient temperature but it is heat-sensitive: it lasts until the material's Curie Temperature (T_C) is reached. T_C is the temperature at which a material undergoes a phase transition and the intrinsic magnetic "moment" of the atoms changes direction to that of the applied magnetic field. This changed magnetism is paramagnetism. Sometimes called induced magnetism, paramagnetism is weak and temporary, and represents a disordered state (the material has unpaired electrons with random spin orientations). Application of magnetic techniques to pottery is not easy, because the ceramics are complex mixtures of many minerals, some of which display paramagnetism and some of which do not.

Electron spin resonance (ESR) or electron paramagnetic resonance (EPR) analyses are related techniques for identifying elements, especially transition-metal ions, on the basis of the spins of their unpaired electrons. When subjected to radiation in a strong magnetic field, the sample absorbs radiation at certain frequencies characteristic of the constituent elements and this absorption spectrum is the basis of the identification of the unknown. Because ESR phenomena are sensitive to heat, this method can be used to estimate pottery firing temperatures (Bensimon et al. 1998; Warashina et al. 1981). ESR and EPR have many other applications including dating pottery (a method similar to thermoluminescent dating), kaolin quality studies (Bertolino et al. 2010), and archaeology in general (Bartoll and Tani 1998).

Magnetic susceptibility was used to estimate the firing temperatures of late pre-Inka and Inka pottery in the Catamarca valley of northwestern Argentina, in the extreme southern portion of the Inka empire (Rasmussen et al. 2012). The procedure used a schedule of long refirings of 36 sherds at incremental steps, measuring susceptibility after each. Plotting a mathematical transformation of susceptibility against temperature yielded a relatively flat line or gentle curve with a sharp discontinuity, the discontinuity indicating the original firing temperature. Two distinct peaks of firing temperatures were identified, at 830°C and 950°C, possibly reflecting two different firing practices

(Rasmussen et al. 2012: 1711). The method, which is claimed to have an accuracy of ±25.5°C, was checked against data from XRD of the sherds and with experimental clay firings.

23.2.6 Fourier Transform Infrared Spectroscopy (FTIR)

A common method of identifying chemical elements is through infrared (IR) absorption spectroscopy, in which a sample is submitted to a beam of infrared radiation energy, which excites the vibrational levels of molecules and atoms. If the energy levels of the sample and the beam are the same, the energy is absorbed; otherwise it is transmitted through the sample. The Fourier transform mathematical technique separates the resultant spectrum of absorption peaks into those unique to specific compounds in the sample. The method has numerous advantages: it is nondestructive and fast (multiple simultaneous measurements), has high precision and sensitivity, can perform qualitative and quantitative analyses, and can be used on organic and inorganic substances. FTIR is typically accompanied by other methods, and has been used with XRD to identify minerals in analyzing Bell beaker pottery in Spain (Odriozola and Martínez-Blanes 2007), with SEM and refiring experiments for more recent pottery in India (Velraj et al. 2009), and with thermal techniques in analyzing clays, bricks, and figurines in northern Europe (Paama et al. 2000).

23.3 Some Cautions

It is appropriate to ask, as many have done over the past half century, Why is there such a desire to determine the precise temperature of firing of one or a few sherds? (Gosselain 1992; Smith 2001; Tite 1969, 1995; Tite et al. 1982: 113). This may be an appropriate goal for studies of museum-quality specimens of the potter's art, but from an anthropological point of view it is neither necessary nor intrinsically significant to know the maximum temperature at which any individual piece of pottery was fired. More to the point are studies of firing temperatures of large numbers of sherds in pyrotechnological characterization studies of wares, types, forms, and so on, to determine patterns, consistencies, and ranges that permit assessment of degree of control of the firing enterprise. These data can then be compared among producing communities, kilns, or other entities of interest.

Firing temperature appears to be a simple proxy or dummy variable, expressed on an interval scale, that can be used to summarize complex interactions typically measurable only qualitatively. Thus several considerations and cautions need to be reiterated.

First: time and atmosphere. The final use-related physical and mechanical properties of a fired ware, such as toughness and durability, are a product of many variables: its composition (the clay minerals and the kind, amount, and size of inclusions and impurities) and the parameters of firing. These last include the time, atmosphere, and temperature during *three* stages: heating, soaking, and cooling. The rate of heating, the rate of cooling, and the total firing duration are all important during these stages. If ancient open firings were at all like those of traditional potters today, the vessels were probably heated to a peak temperature and then, rather than being held (soaked) at that temperature for any significant time, allowed to begin cooling in fewer than 30 minutes.

Second, in terms of implicit comparisons with the thermochemical behavior and thermal properties of clays or clay mixtures in a testing laboratory, the characteristics of these latter are developed under conditions approaching equilibrium. That is, the slow rate of heating and the extended period of holding the materials at a specified temperature—sometimes for one hundred or even two hundred hours—in a lab usually allows completion of mineral and chemical alterations or reactions occurring within the constituents of that system at that temperature. The samples being fired are of known and uniform composition, and they and the testing procedures themselves are subject to national or international standards for comparative purposes. No further changes occur unless the conditions are changed—for example, if the temperature is raised. Under lab conditions as well as among studio potters using electric kilns, the clay bodies are fired to maturity: the maximum hardness and minimum porosity of a particular clay body or glaze composition or ware. In the rapid mixed firings common in many parts of the world, past and present, however, the earthenware clay body does not even approach maturity.

Third, an important consequence of this experimental (quasi-)equilibrium and maturity is that the thermal gradient within the ceramic wall is eliminated during firing, as are differences between inner and outer surfaces. This raises a significant question with respect to pyrometric studies of open firings of traditional potters today, and by analogy with ancient firings: Given the extremely short firing times, are the measured temperatures actually attained by the vessels throughout their walls (eliminating a thermal gradient) or are they simply the temperatures of the fire surrounding the pots (Nicklin 1981a)?

Related to this, the temperature at which sintering begins, for example, is highly variable, given the clay's refractoriness, impurities, particle sizes, and the atmosphere of firing; and it might have occurred at temperatures that remained high during the early stages of slow cooling but below the maximum. Vitrification may occur over a temperature range of 200°C (Tite and Maniatis 1975a).

Finally, the temperatures attained in nonindustrial firings—open fires and kilns alike—are apt to fluctuate considerably. Even within kilns, temperature differentials of as much as 100°C may exist from top to bottom or from the center to sides (see, e.g., Mayes 1961, 1962). If a vessel were fired in a reducing rather than an oxidizing atmosphere, the actual firing temperature could be as much as 50°C lower than the experimental estimate; if it had a shorter heating and soaking time, the firing temperature may be 50°C higher (Tite and Maniatis 1975a: 122).

A great deal of analytical expertise has been devoted to developing ways to assess the original firing temperature of a sherd. Each method has particular drawbacks and indeed several problems are inherent in the entire enterprise. One difficulty is that many of these methods depend upon prior knowledge of the clay mineral constituents of the sherd. But earthenwares recovered archaeologically were made of clays that were not likely to be mineralogically pure kaolins or smectites, for example. A given reaction can occur at different temperatures in different clay minerals. Similarly, the pottery of interest may have a variety of mineral inclusions added as temper and these too may undergo thermal reactions. Although knowing the temperatures at which these reactions occur in mineral inclusions might be useful in estimating firing temperatures, there may be confusion in separating them from clay minerals (see Isphording 1974: 482).

In addition, analyzing the properties of a pottery fragment recovered from an archaeological site yields information on its current properties, and one might ask whether these are equivalent to the ancient properties and hence a valid basis for estimating firing temperature. Postdepositional processes—leaching, mineral recrystallization, rehydration—might affect the properties measured to estimate the original firing temperature. The possibility of rehydration during burial is of particular interest (see Flamini and de Lorenzo Flamini 1985). The loss of clays' crystalline structure during firing because of elimination of lattice water had long been thought to be nearly complete and permanent. However, this limitation may be incomplete or reversible, or vary with individual clay minerals, and pottery fired between 500°C and

800°C may rehydrate and reverse the structural changes (Grim and Bradley 1948; Kingery 1974; Magetti 1982). This means, at least in theory, that the sherds can be examined by certain techniques, such as XRD or DTA, which will identify the original clay mineral(s), but the associated firing temperature information might be lost.

Another concern is the accuracy of the archaeothermometric methods, some of the older of which may vary as much as ±100°C (Tite et al. 1982: 113). This means that if the firing is estimated to be 800°C, one can only claim that it was probably fired between 700°C and 900°C—which is the common range for most firings by potters today using traditional technology (Smith 2001; see also Gosselain 1992: 244).

The use of multiple techniques to estimate original firing temperature is a useful archaeothermometric strategy. For example, combining SEM and porosity determinations will be informative about not only the firing temperature, but also the extent of vitrification. As such, these techniques consider the important roles that microstructure and mineral or chemical additions play in developing the physical properties scrutinized in assessing firing temperature, measuring not only a technical property of the ceramic but also cultural and functional characteristics. If vitrification is consistently attained, as determined from analyzing many samples of a particular type or ware, this reflects advanced development of firing control among the producers (task specialization?) as well as consumer demand for hard, nonporous vessels.

Given the variability inherent in traditional (non-industrial) firing, what is important is not the determination of a single variable of original maximum firing temperature, but rather the consistent attainment of a particular firing range in a particular category of ceramic. This information, which must be obtained from large numbers of sherds, provides a useful clue both to potters' general control over their pyrotechnologies and to the consumers' expectations or desires for the quality of the products. The concept of "equivalent firing temperature" was long ago suggested as more appropriate than attempting to determine precise temperatures of prehistoric firings (Tite 1969). Similarly, the notion of "work heat" (Nelson 1984: 270) calls attention to the need to consider both atmosphere and time, along with temperature, in understanding the character of a finished ceramic object.

24 Style and Social Interaction

> Pots were made in the Bé style "because that is how pots are made at Bé."
>
> David and Hennig 1972: 27

The surfaces of clay vessels can be manipulated in many ways to alter the texture, color, and overall appearance of the formed piece (sec. 8.3, chap. 9). These surface manipulations, alone or in combination with other attributes, are the basis for defining decorative styles of pottery and these styles, in turn, are a traditional basis for many anthropological and archaeological inferences about social and economic interactions, artistic communication, and the dating of sites. Innovative approaches to pottery styles and their interpretation flourished in American archaeology from the mid-1960s through the early 1990s (see Hegmon 1992; Plog 1980), then fell off, and now new considerations are emerging. This chapter reviews some approaches to pottery style, including decorative style and stylistic analysis.

24.1 What Is Style?

A complex concept applied in numerous disciplines, style, like art, is difficult to define precisely (on art, see, e.g., Morphy and Perkins 2006; Silver 1979; on style, see, e.g., Munn 1966; Schapiro 1953). The term style is perhaps used most frequently in the arts and literature, where it is an abstraction with two primary senses. One sense considers style to be a manner or mode of expression, "a way of doing something" such as sculpting or dancing or dressing (Conkey and Hastorf 1990: 2–3; Hegmon 1992: 517; Hodder 1990: 45). As such, style is practice and is closely related to technology, another "way of doing" (Franklin 1999: 6). A second sense of style focuses on the formal or visual qualities of that expression: its distinction, originality, and character, as in a building's architecture or a painting's use of light. Both senses call attention to the special skills of an individual artist (writer, architect, composer) and the creation of his or her oeuvre. A third sense of style is more specific: distinct styles characteristic of particular times or places, expressions that are typically embedded in broader cultural contexts, such as "Olmec style" or "Renaissance style" (see Knight 2013: 23–25, 177).

Anthropological and archaeological studies of pottery incorporate these senses of style—practice/execution/technique, formal/visual quality, and cultural context—but attention is also directed toward a fourth sense: content and "meaning." A decorative style communicates through its visual elements: its images, representations, and icons (Knight 2013). Aside from technological styles, pottery style usually denotes decorative style, that is, the surface embellishment of an object, and combines all four senses.

One key component of a decorative style is the characteristic way the artist defines the space to be embellished and the way that space is filled (or not filled: negative space). These decisions are indicated by various terms used to describe styles, such as representational, naturalistic, realistic, abstract, iconic, or geometric (see, e.g., Munn 1966). The latter three—abstract, iconic, and geometric (e.g., fig. 1.2)—are applied to styles in which the subject has been reduced to a selection of particular features regarded in some way (usually in symbolic content) as essential or basic; the full visual character is not elaborated. The first three—representational, naturalistic, and realistic—refer to pictorial styles that portray their subjects more or less accurately, with emphasis on form (e.g., figs. 1.4, 1.5).

In addition, the relative degrees of realism in art and art styles have been differentiated. Although two-dimensional art rarely is truly realistic, representational forms (e.g., of animals) differ in how much the parts of the design are distorted to fit the space (Holm 1982). "Configurative" expressions try to achieve an essentially realistic likeness with little distortion. At the other extreme are "distributive" styles, which sacrifice a realistic image to a *horror vacui,* a need to fill a given space completely, so that the relationship of the parts is greatly distorted. "Expansive" designs fall in the

middle: there is some distortion in the image but less insistence on filling all the available space.

Peter Roe (1995: 30–31) identified eight components that both interrelate the material and process senses of style, and also combine the individual or personal variables of the agent artist with those that are part of a broader culture. These components are as follows:

- Recognizability: A style is identifiable by certain distinctive traits. [These may be visual, tactile, or auditory.]
- Workmanship, virtuosity, skill: "If more time is spent on these traits than is necessary to satisfy utilitarian imperatives, they are stylistic features."
- Medium or vehicle: Style is a "medium-dependent process, although it may structure different media in similar ways" [as, for example, Arts and Crafts furniture and architecture].
- Historical context: Styles are particular to certain times and places. [This is why we are able to distinguish Art Deco from Bauhaus architecture, and why pottery styles date sites or occupations.]
- Choice of elements or components: Elements are part of systems with known alternatives and rules of combination; some are variant and some invariant. [It is these choices that enable styles to contain and send information.]
- Normativity or standardization: Style must meet the expectations of the target audience [users or "consumers" in the case of pottery].
- Corpus: Style does not reside in unique artifacts or singularities, but in sharing and repetition.
- Affect: Styles represent a balance between creativity and tradition.

On the one hand, then, styles may be thought of as culturally structured or standardized in some manner. Features are selected from within a relatively narrow body of interrelated technical, thematic, and aesthetic alternatives, and combined through a set of rules grounded in tradition and group identity, and based on ethnicity, religion, political alliances, or other factors. All of these are, by tacit consensus, peculiar to a given cultural system: "because this is how pots are made at Bé," explained the potter to the anthropologist.

On the other hand, this structuring does not equate with rigid conformity or homogeneity. Styles are open rather than closed systems of expression, constantly receiving and transmitting new information. They are not fixed, static entities: rather, styles have dynamic and individual aspects. Variations are found within styles not only because a range of alternatives exists but also because there is some flexibility in their application. Certain styles or style variants may be appropriate to particular behavioral contexts. The degree of free choice or idiosyncratic variation allowed within styles is culturally significant: societies differ in how much departure is permitted from the norms of their particular traditions, in the acceptable sources of such innovation, and in the contexts in which such variants may appear. These features are particularly important to archaeologists in any long-term perspectives on cultural change.

Hypotheses advanced to account for the development of styles and their maintenance within particular societies have called attention to myriad determinants, which can be organized into hierarchies of attributes, processes, constraints, and contents (Carr 1995). Factors may be social, psychological, and environmental, and include technical

evolution, historical diffusion, settlement patterns, environmental pressures, child-rearing practices, presence of sex-specific social groups, individual personality structure, creativity, perception, age, physical attributes such as motor skills, and wish fulfillment (see, e.g., Bleed 2008; Fischer 1961; Hill 1977; Roe 1995; Voss and Young 1995; Wolfe 1969). These factors are also important in the transmission of styles. Potters and painters of pottery operate within a decision hierarchy: their choices may be influenced by other technologies or practices, and their previous choices may constrain subsequent ones (Carr 1995).

Insights into the influences underlying individual creative impulses and their effects on stylistic change in pottery have come from ethnographic studies in various areas: tropical Peru (Lathrap 1983), highland Guatemala (Reina 1963), the Southwestern United States (Marriott 1948), and Africa (Thompson 1969). But addressing individual styles in antiquity requires not only isolating significant attributes of the general style from other aspects of variability (use, manufacturing technique, skill, etc.) but also distinguishing variations among artisans (see Hill and Gunn 1977). Individuals may be differentiated if their output was copious, if they left distinguishing marks (fig. 24.1; Arnold 1972; Donnan 1971; Gill 1981; Man 1894: 26; Potts 1981), or, best, if they signed their work by name or workshop affiliation as in some Greek (Beazley 1945; von Bothmer 1985), Roman (Dickinson and Hartley 1971; Hartley 1966; Johns 1963), and Maya (Reents-Budet 1994) pottery. In some cases, decoration itself may serve as a potter's mark, as in the Philippines, where the number of painted bands identified a particular potter's output in a communal kiln load (Scheans 1977: 65). Countless ethnoarchaeological studies have claimed that potters are able to recognize the products of other potters in ways that typically elude archaeologists.

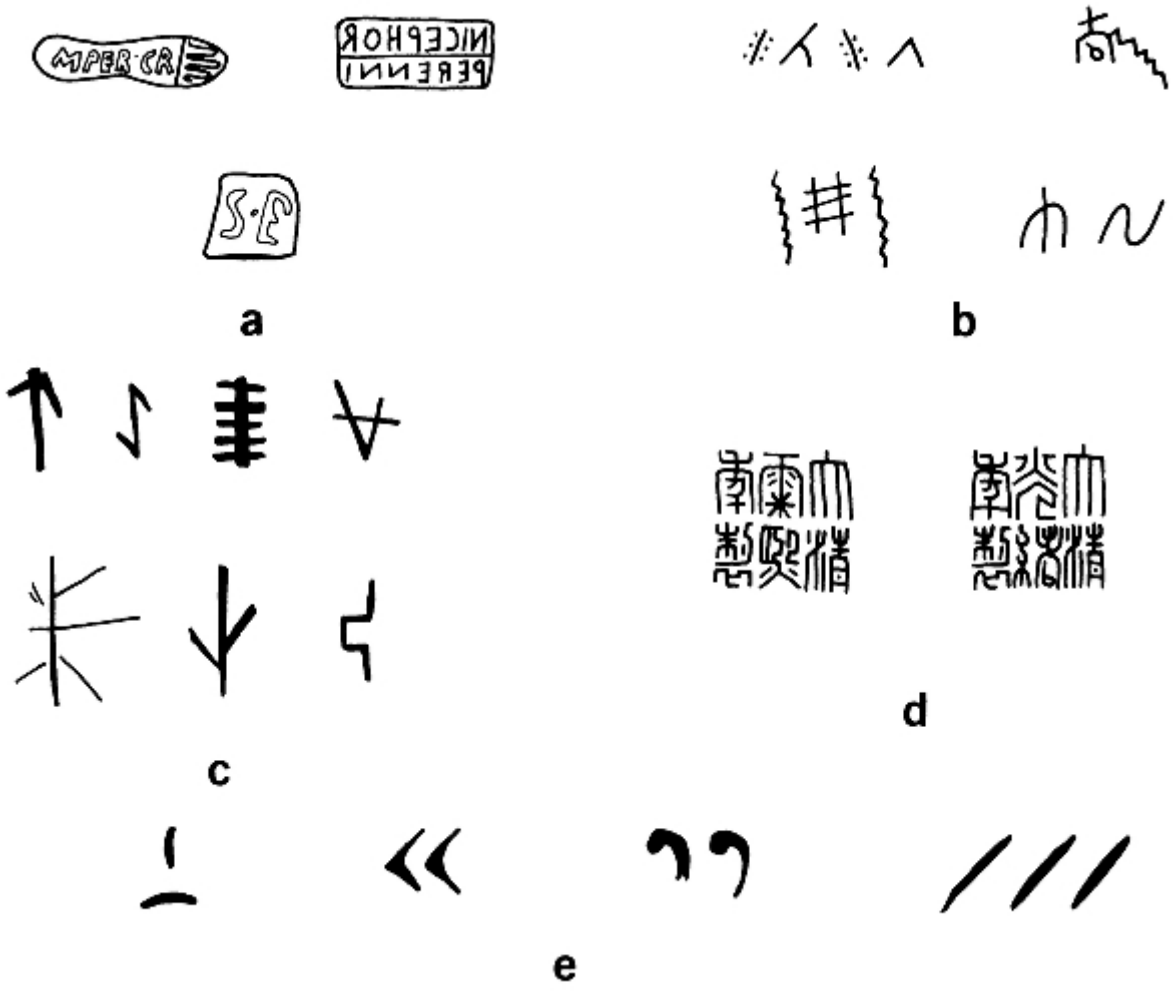

Figure 24.1 Potter's marks and stamps (not to scale): *a*, Arretine stamps; *b*, Yangshao pottery marks from Banpo, China; *c*, multisign "inscriptions" on pottery from Tepe Yahya, Iran; *d*, Chinese porcelain marks (*left*, K'ang-hsi, 1662–1722; *right*, Kuang-hsu, 1875–1908); *e*, marks on Moche pots from Peru. Sources: *a*, after Peacock 1981: fig. 61; *b*, after Cheung 1983: fig. 12.1; *c*, after Potts 1981: fig. 2; *d*, after Medley 1976; *e*, after Donnan 1978: fig. 3i, l, n, q.

Complex, painted representational and realist styles may provide the best opportunity to discriminate individual artists, because there are more steps in their execution and hence greater opportunity for idiosyncratic and perhaps unconscious variation (see Hardin 1977; Hill 1977). Otherwise, heuristic categories such as "microstyles" (Muller 1977) or the "analytical individual" (Gunn 1977: 168; Redman 1977) may be the smallest constellation of stylistic consistencies that can be reliably isolated in the archaeological record. Although these do not necessarily correspond to the work of a single individual, their high level of similarity may reflect task or production units.

24.2 What Does Pottery Style Do?

Early analytical efforts to understand the relations between decoration and the originating society frequently divorced the formal or visual qualities of a style from its content or "meaning." For example, traditional approaches to pottery focus on identifying formal qualities, grouping vessels or sherds into classes or types by the presence/absence of certain features such as motifs or techniques. These categories are then used to reconstruct local and regional site sequences through seriational arguments of relative similarities and inferences of gradual stylistic change. The geographical distributions of particular stylistic components or combinative styles on pottery also permit hypotheses about contacts between sites or regions. Where the areal spread of a style is especially extensive within a relatively brief period, it is often referred to as a horizon style (see Willey and Phillips 1958: 31–33).

Studies of the meaning or content of styles, on the other hand, address the ways they —and art in general—express deep-seated characteristics or beliefs of the society that produced it. Thus the meaning of a style can be construed on several levels. At one level, style is seen as a reflection of aesthetic preferences, conscious or unconscious; at another, style is considered to mirror significant features of the natural and social environment. Particularly useful where artistic expression (ceramic or other) is strongly representational, these approaches frequently address natural, mythological, or iconographic themes (e.g., Bankes 1980; Coe 1978; Knight 2013; Lathrap 1973; Mera 1937; Proulx 1968; Pyne 1976; Thompson 1969). A third level of meaning sees the content of styles—both visual images and spatial arrangements—as a symbolic code reinforcing social and cosmological structures, beliefs, and values. Decorative styles can be seen as a kind of visual communication that reproduces the principles and relationships by which a community structures and organizes its perceptions of social realities and the cosmos, and orders experience into coherent categories (Munn 1966). In this view, the long-standing dichotomization of style and function is erased: styles and their variants function in communicating ideas, concepts, and other kinds of information coded into the decoration.

24.3 Archaeological Approaches to Pottery Style

Beginning in the 1960s, decorative style was accorded increasing importance among Americanist archaeologists who sought to explain variability in the archaeological record in terms other than comparative dating (fig. 24.2). It was within this movement that debates began over whether style was "merely stylistic" or did it also "function," and how style relates to technology (Binford 1965: 199–203; Dunnell 1978; Sackett 1977a, 1982, 1986). Several approaches to analysis and interpretation of pottery decoration were developed in the 1960s and 1970s, the most influential of which focused on design elements. Design element analyses, their critiques, and recommendations for improvement aided the development of subsequent approaches to ceramic stylistic analyses (see Skibo 2013: 68–74).

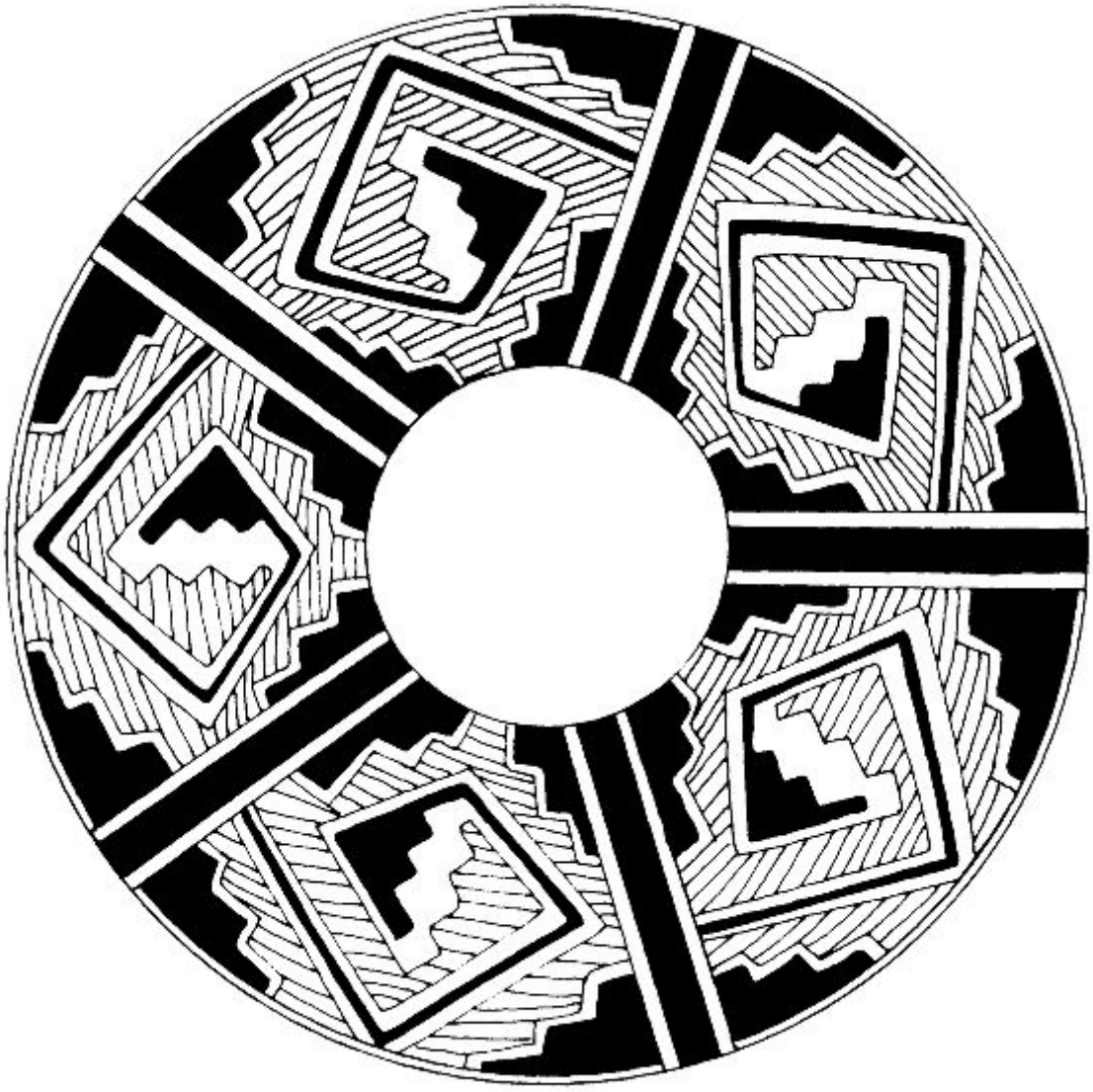

Figure 24.2 The design configuration of a black-and-white vessel from the El Morro Valley, New Mexico. After Redman 1978a: fig. 4.3.

24.3.1 Design Elements and Social Interaction

A design element is the smallest self-contained component of a design that is manipulated or moved around as a single unit (fig. 24.3). An element may correspond to a single stroke of a painter's brush or cut of an incising tool, or to several such steps. Design element analyses were based on what has come to be known as the interaction hypothesis, the social interaction theory, "ceramic sociology" and "ethnic iconography" (Sackett 1977a: 376, 377), and, after its earliest and best-known exponents, the Deetz-Longacre hypothesis. This proposition holds that the similarity (or comparative frequencies) of design elements between groups will be proportional to the direction and intensity of social interaction between members of those groups.

The interactions of interest—descent and residence, intermarriage, teaching-learning patterns, religious or economic contacts—may occur between members of different social subgroups (clans, families, residence compounds) within a single community or site or between different sites or communities (e.g., Deetz 1965; Longacre 1964, 1970; Whallon 1968). Analyses attempted to explain the spatial occurrence of design elements in terms of the social behavior of the makers and users of the pottery. Early studies were carried out primarily in the American Southwest, but the approach has also been applied in other areas.

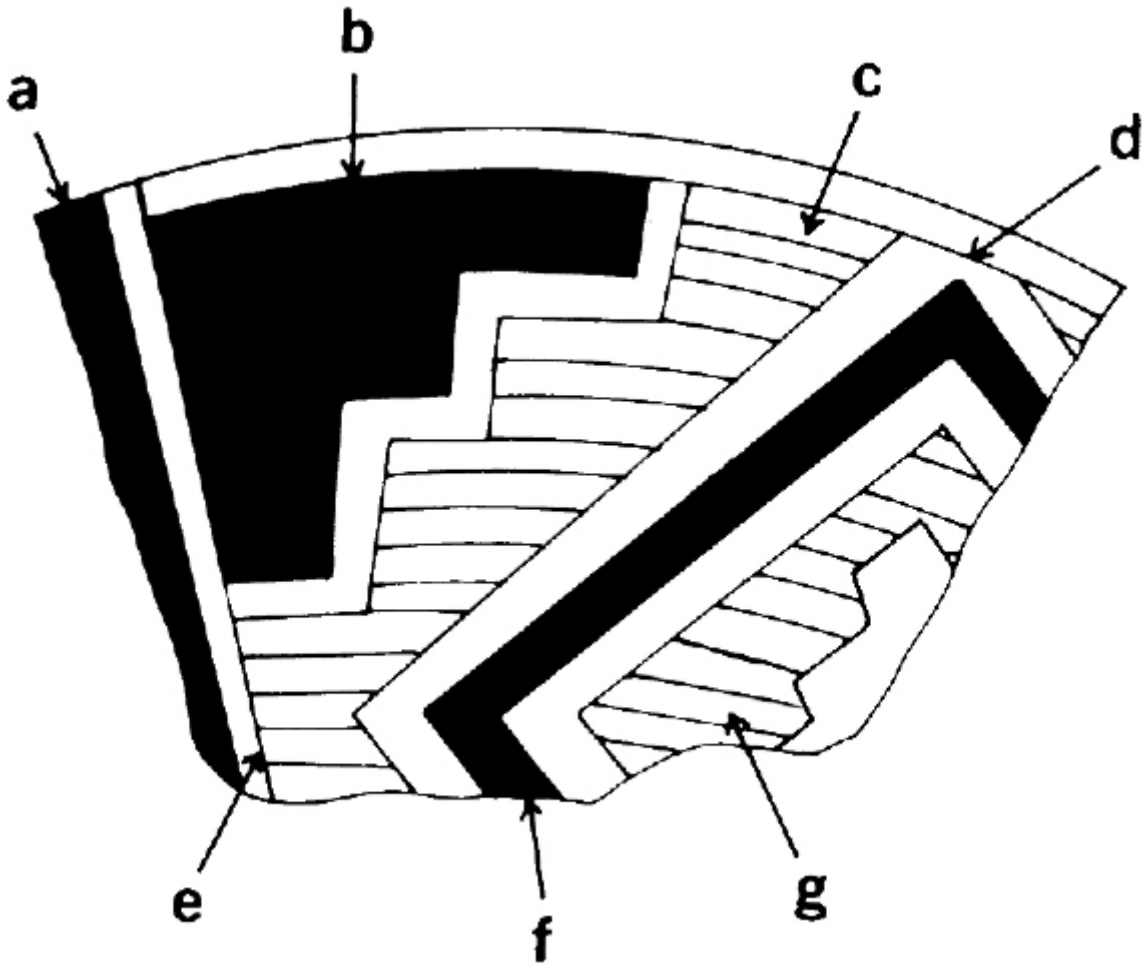

Figure 24.3 Some individual design elements in the vessel shown in figure 24.2: *a*, single straight band, touches rim; *b*, single solid step; *c*, obliquely hatched, straight-based, merging, isosceles triangles; *d*, single rim line, does not touch rim; *e*, single straight line, touches rim; *f*, single solid angle band; *g*, single obliquely hatched step.

Design element analysis received substantial criticism (e.g., Hodder 1981; Plog 1978; Washburn and Ahlstrom 1982; Watson 1977). One critique concerned the social interaction theory itself: Did styles primarily reflect social relations or were they were equally responsive to other phenomena? Was there a direct correlation between stylistic similarity and the intensity of social interaction? Styles, whether in ceramic decoration or in some other medium, may reflect social interactions, but do so neither necessarily nor exclusively. The Hopi and Hopi-Tewa, for example, live in three contiguous villages but have different languages, religions, and social patterns; nonetheless they manufacture identical pottery (Stanislawski 1978: 225–26). In contrast, in sub-Saharan Africa, pottery and other categories of material culture evidence complex patterns of similarity and difference across tribal and linguistic boundaries (Gosselain 1998; Hodder 1977; MacEachern 1998). Clearly, physical proximity and potential or actual social interaction alone do not determine stylistic similarities.

Ethnographers and ethnoarchaeologists identified other flaws: oversimplified assumptions and inattention to intervening factors in inferences about descent and residence, patterns of learning, and archaeological site formation. For example, initial studies were based on retrodicting the matrilineality and matrilocality of contemporary Puebloans into the past. But residence rules are idealized constructs, making the likelihood of finding a purely matrilocal community slim (Allen and Richardson 1971). From the viewpoint of site formation processes, spatial dislocations resulting from discard and recycling of broken vessels weaken the underlying premise of the interaction hypothesis. The disposition of pottery styles within and between sites can result from socioeconomic arrangements other than personal interaction intensity (e.g., Balfet 1965: 166; Plog 1976: 256–59, 1980: 54–76).

A second broad area of criticism of ceramic sociological studies was methodological, raising three specific concerns: defining elements, sample size, and statistics. How to define the design elements and construct a typology of them was particularly problematic. Although elements need not be the irreducible minimum of design, it was difficult to separate elements from larger, more inclusive units such as motifs, and the defining criteria were often vague and subjective (e.g., Plog 1978: 159). Some researchers shifted their attention to variability within and between elements, for example, in the elements' attributes (Deetz 1965; Plog 1980; Redman 1978: 175), but analysts often disagreed: an element to one person might be an attribute or even a motif to another.

Concerns about sample size in these analyses related to the wide range of variability in the objects of study—elements, attributes, motifs, types, and forms—and their variation with location or period. Large numbers of sherds or whole vessels needed to

be analyzed from each unit of interest, along with some type of minimum number of vessels (MNV) estimates rather than individual sherd counts. Related concerns addressed the statistical procedures used in calculating similarity and in comparing sites or other provenience units. Methods varied from simple visual comparisons and contingency tables to multivariate analyses such as factor or cluster analysis. Errors resulted from inappropriate assumptions concerning the data distribution and arbitrariness in distinguishing significant from nonsignificant results (Plog 1978: 166–77).

24.3.2 Hierarchical Design Structure Analysis

Use of space—the spatial arrangements or structuring of the designs on pottery or other decorated objects—is of interest in virtually all approaches to analyzing style. The hierarchical design structure analysis (HDSA) approach is concerned with the sequence of procedures or decisions that artisans follow and their rankings of spatial divisions of the surface of the pot (Friedrich 1970: 342; Plog 1982; Redman 1977, 1978; Roe 1980). Conceptually, design structure refers to the cognitive system, or body of organized knowledge, underlying a particular style and through which it is produced. Empirically, the decorative structure or layout (fig. 24.4) refers to where the decoration appears—whether the area is subdivided, whether and how it is bounded, the symmetry and balance of the decoration, the amount of space covered, and the placement and relations of different components (fig. 24.5).

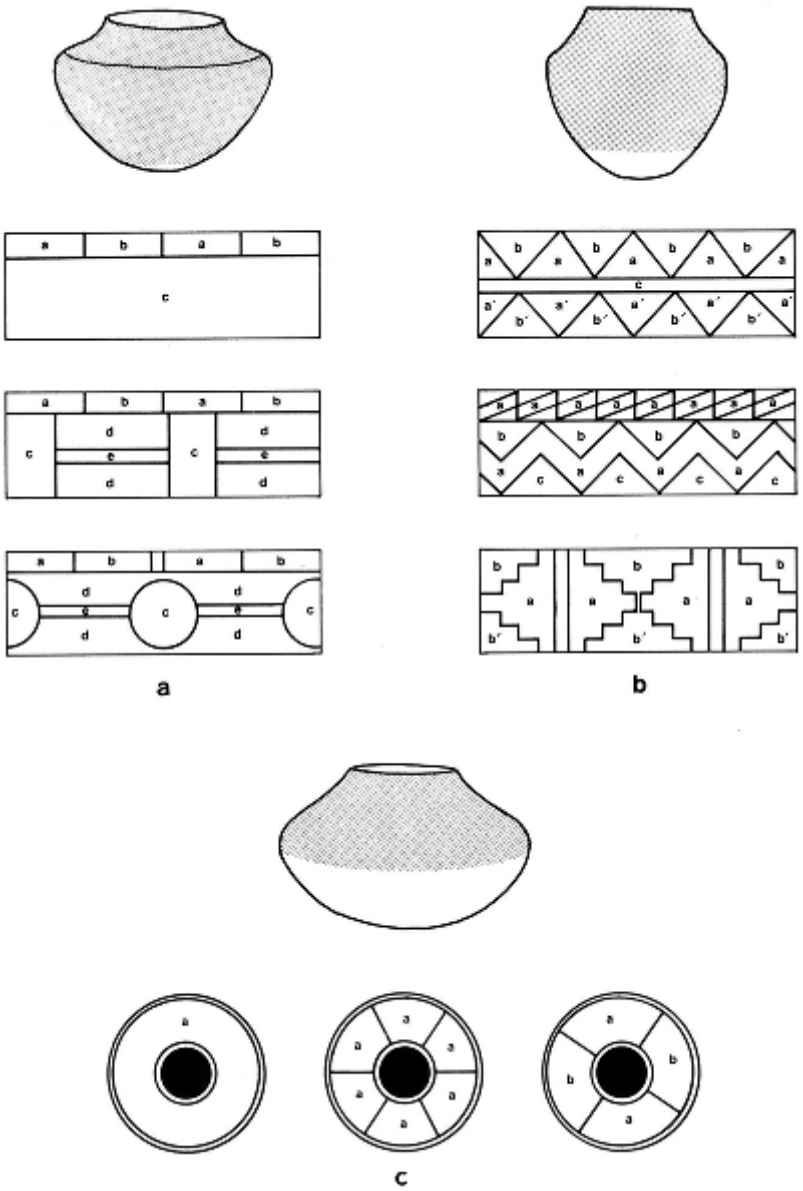

Figure 24.4 Modern Pueblo (Southwestern United States) jars and their design arrangements. Area of design on vessel is shown by stipple; small letters within zones indicate particular designs and their repetition: *a*, Zuni—jars have two contiguous units of decoration, neck and body, and clear distinctions as to the designs that belong in each; *b*, Acoma—although the jars are nearly the same shape as Zuni jars, the entire jar is a single design space and is covered with elaborate motifs emphasizing the diagonal (see also fig. 1.11); *c*, Hopi—the shallow, squat jars are decorated on the upper shoulder, presenting a ring-shaped field that can be viewed in its entirety in painting and use. Sources: *a*, after Bunzel 1972: plates III*a*, II*a*,*b*,*c*; *b*, after Bunzel 1972: plates XI*f*, XIII*a*, XII*d*, XIII*b*; *c*, after Bunzel 1972: plates XV*a*, XVI*a*,*b*,*c*.

The structural components of decoration—elements, motifs, configurations, and basic units—are categorized as either primary or secondary by their order of execution and prominence in the overall design (Friedrich 1970: 335; Hardin 1983; Plog 1980: 53, fig. 4.4). Configurations are arrangements of motifs to fill a spatial division, constituting a visual complex that is recognized as "the design." Basic units are the most immediately recognizable components of a design, and so may be easily borrowed or imitated from artist to artist. They may correspond to different design levels in different

communities, although they are easier to envision in terms of the larger units of motifs and configurations. Basic units are categories in the mind of the artisan and thus difficult to work with in archaeological contexts because of subjective inference. A completed HDSA has four components: definition of the area to be decorated, that is, the "decorative problem" (fig. 24.6), identification of the basic units of decoration, classification of the basic units, and identification of the rules by which the basic units are used to solve the decorative problem (Hardin 1983: 9).

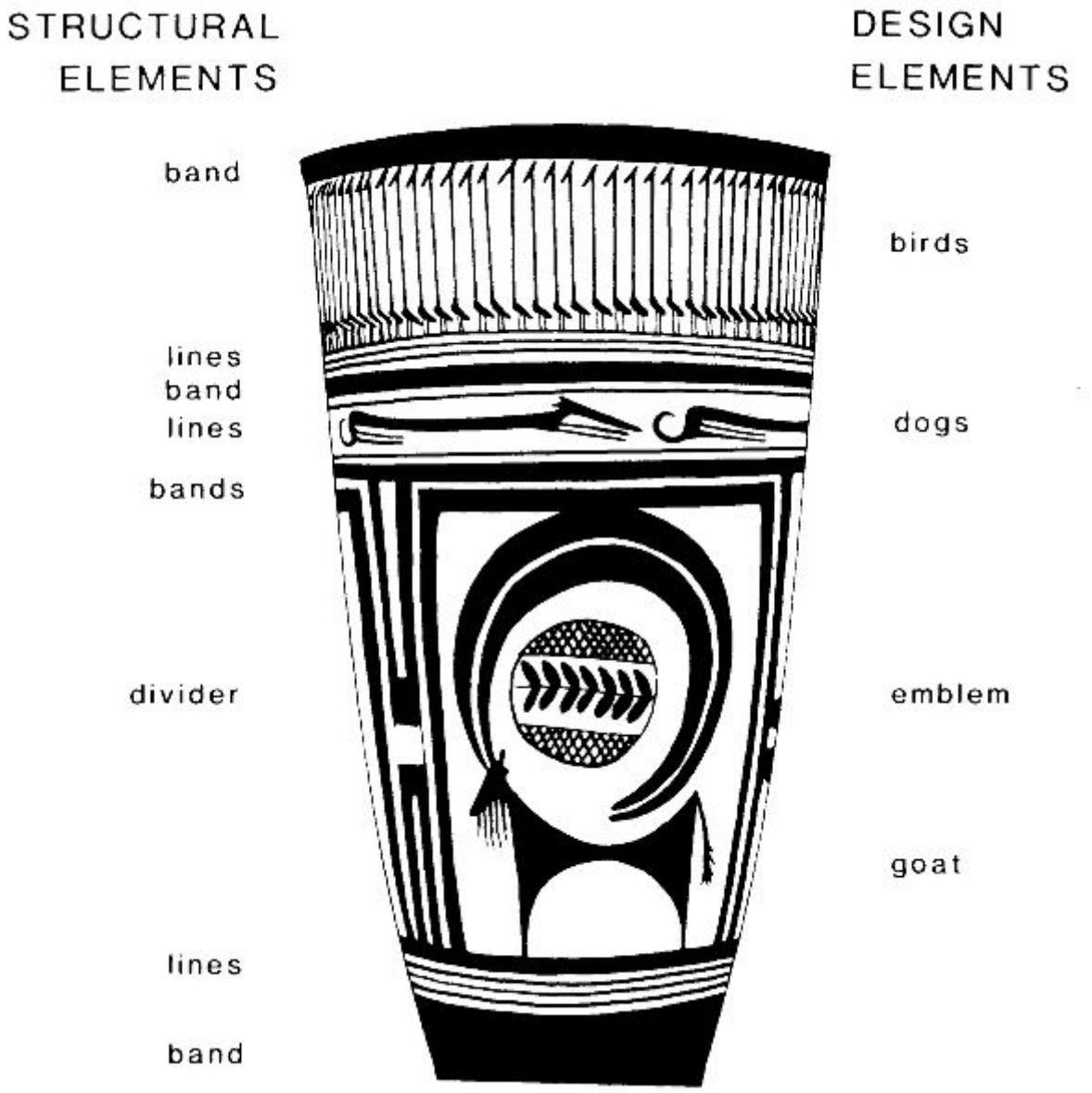

Figure 24.5 Structural and design elements on a Susa (Iraq) beaker. After Hole 1984: fig. 2.

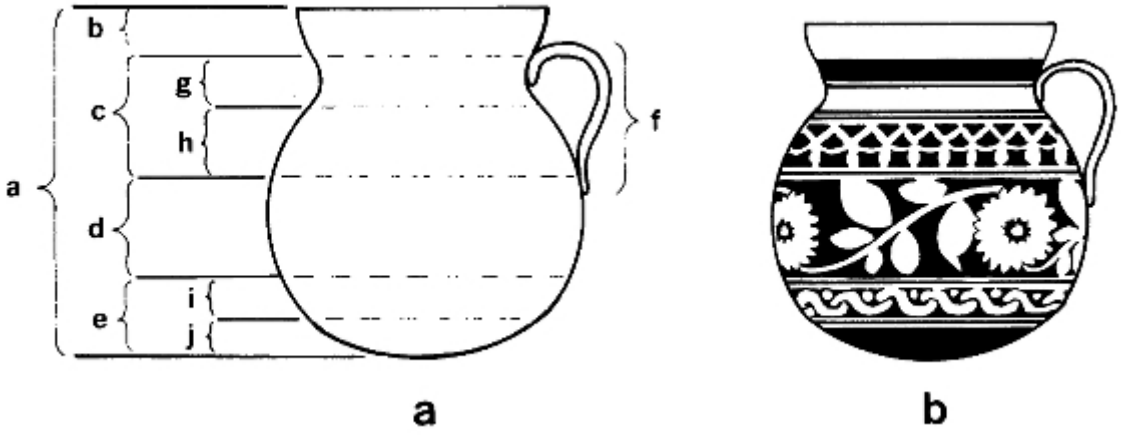

Figure 24.6 The system of spatial divisions underlying the painted decoration on Tarascan (Mexico) ollas: *a*, named parts of exterior (*a–f*, major divisions; *g–j*, subdivisions); *b*, painted designs, showing different designs in each division and subdivision. After Hardin 1984: figs. 1, 2.

Cultural patterning can be seen at varied levels of the hierarchy. The location of decoration in general or of different kinds of decoration clearly relates to how a vessel is viewed and used, but layout may be studied with the aim of relating it to other structural patterns in the society. For example, one of the tenets of design element analysis was that stylistic similarity (sharing of elements) reflects the intensity of interactions between various groups of people. In HDSA, elements, motifs, and configurations are not viewed as useful indicators of interaction intensity because they are too easily copied and exchanged with even minimal contact between artists. Instead, it is their spatial relations on a vessel—the design structure, and especially the presence and location of boundary markers—that relate to community identifications and standards (Friedrich 1970: 338–39).

Because HDSA was developed by ethnoarchaeologists, it has benefited from the complementary joining of the analysts' observations with informants' verbal information on how basic units are classified and the rules for combining them in decorating a vessel. Not only has this provided a fuller picture of the "design grammar" underlying stylistic structure, but it has suggested specific features of artists' interactions and executions relevant to style analyses. Study of the pottery manufactured in Quinua, highland Peru, combined a structural approach with symmetry analysis (Arnold 1983, 1984). The structural relations in the designs on four classes of vessels reflect differences among the communities producing them. This supports the notion that because design structures are more closely identified with producing groups than are elements, they are more stable indicators of interactions than elements, which transfer readily. More recently, HDSA was applied to the painted decoration on Spanish majolicas and their New World tin-enameled ware copies in Mexico, Central America, and the Andes (Rice and Natt 2013). This analysis upheld the major tenets of the approach in revealing the similarities of motifs and differences in color combinations

and boundary use with distance—spatial, temporal, and religio-ethnic—from the Spanish homeland.

24.3.3 Symmetry Analysis

Symmetry or pattern analyses of pottery style emerged in the late 1970s after being pioneered decades earlier (Brainerd 1942; Shepard 1948b). Unlike methods that begin with objects, symmetry analysis begins with the mathematical principles underlying the three-dimensional crystalline structure of atoms. Design is described with respect to the spatial position of geometric figures and their movement with respect to a line or point axis. Neither the figures themselves nor the decorative field of the vessel—its location, shape, or size—are of primary interest.

Symmetry analysis begins by identifying the basic unit of the design: "the unique part of the pattern from which the entire composition can be generated" (Shepard 1976: 268; see Washburn and Crowe 1987). It may be a motif or an element in conventional terminology. The next step is to determine the repeated motion or transformation of that part around a real or imaginary point or line to form the design. Four kinds of movement define four classes of symmetry (fig. 24.7):

- Translation: the simple serial repetition of the element or part along a straight line with no change in orientation.
- Bilateral symmetry (reflection or mirror reflection): the repetition of an element as if reflected across a mirror plane, which may be oriented vertically, horizontally, or diagonally.
- Rotational symmetry: the rotation of the design unit around a point; typically bifold, with a rotation of 180° so that the elements essentially oppose each other. Rotational symmetry may also occur in multiple (threefold, fourfold, and sixfold) forms.
- Slide or glide reflection: a combination of reflection and translation.

If a design is composed of only one nonrepeated fundamental part, it is said to be asymmetrical.

Geometric decoration can be described in terms of these motions with respect to single or multiple points or axes:

- Finite design: movement around a single point.
- One-dimensional infinite design (a band): movement repeated along a straight line, most commonly by translation or bifold rotation (e.g., fig. 24.5, top).
- Two-dimensional infinite (allover) design: any symmetry movement except translation. On pottery surfaces, decoration is, of course, always executed in only two dimensions, even though those surfaces may have a pronounced curvature. Similarly, the decoration is not truly infinite because it is limited by the vessel dimensions.
- Countercharge (color reversal): painted decoration with color or filling (e.g., hachure) alternating in some way.

Symmetry may be imperfect, because of careless execution, asymmetrical curvature of the surface, deliberate intent, such as adding embellishments (fig. 24.8), or countercharge.

Symmetry analysis has been used to describe pottery decoration in the Southwestern United States (Washburn 1977, 1978; Zaslow 1977; Zaslow and Dittert 1977) and Mesoamerica, particularly in comparing designs between these areas (Brainerd 1942; Shepard 1948b; Zaslow 1981). Applications also include styles of Neolithic Greek and Aegean pottery (Washburn 1983), early ceramics from Ban Chiang, Thailand (Van Esterik 1979), and modern pottery from Ecuador (Bowser 2000). Symmetry analysis has been incorporated into broader analyses of structural relations in representational and nonrepresentational patterns through metric and geometric transformations (Bowser 2000: 233; Washburn 1995).

A claimed advantage of pattern or symmetry analysis is its objectivity in classifying and describing designs by mathematical terms rather than verbal descriptors such as herringbone or chevron. For example, decoration may be described by a positional (three-digit) alphanumeric notational system of prefixes, superscripts, and subscripts: a "Class 1–$2^2$00" pattern is a one-dimensional infinite design with two rotations around the principal axis (bifold rotation) and countercharge between figures along that axis (Washburn 1978: 110). That is, the design features two rows of opposed right triangles, one solid black and the other hatched. A different notational system describes a "pgg" symmetry class common in the Southwest, in which "glide lines alternate with rows of two-fold axes" (Zaslow 1981: 11).

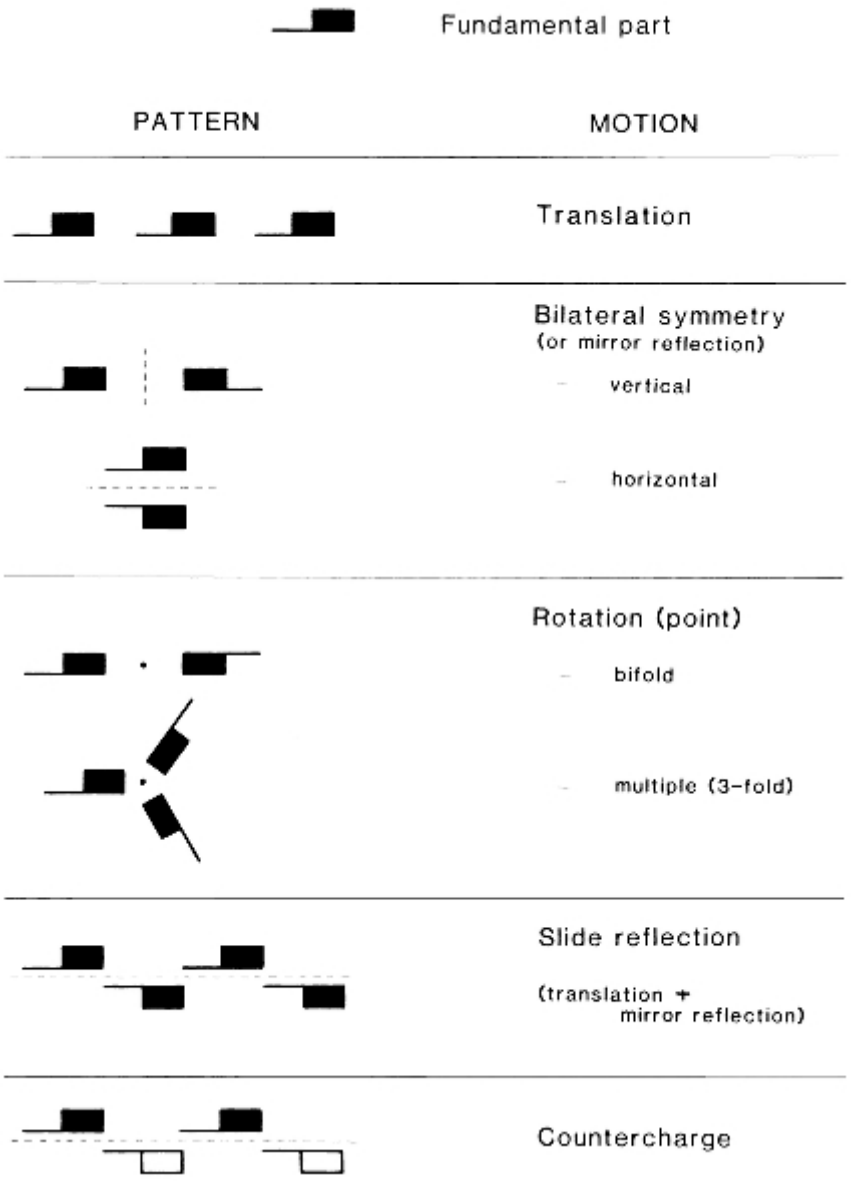

Figure 24.7 Symmetry classes and motion involved in producing different design patterns from the fundamental part illustrated.

Although different cultures may exhibit different symmetry or pattern mathematics behind their decorative systems, it is unclear what these differences (or similarities) mean. Interpretations generally assume that a pattern is shared, passed through generations, and thus sensitive to time-space variation. Differences may relate to indigenous versus introduced stylistic change and production, marketing, or long-distance trade relationships (Washburn 1983; Zaslow 1981). It is also unclear if or how readily symmetry patterns, as opposed to motifs, are transmitted and integrated into local styles. If a motif is associated with a particular symmetry system in one area, its presence in another system with different symmetry principles suggests that it was added from its original area (Brainerd 1942: 165). Alternatively, a pattern copied from one area into another will spread as the artist deciphers basic construction principles, but the embellishment is likely to be in the local style (Zaslow 1981: 39).

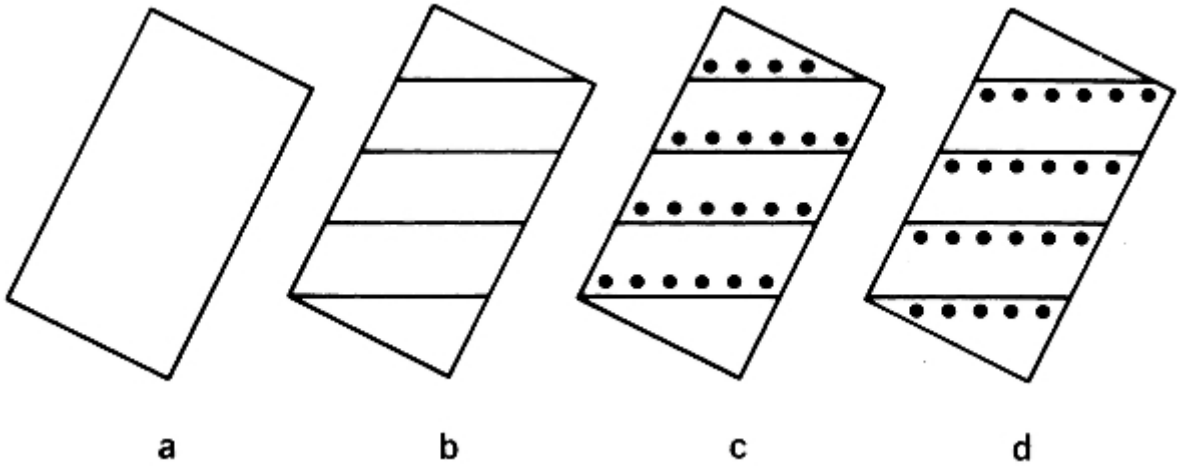

Figure 24.8 Change in design symmetry by addition of embellishments: *a*, rectangular element; *b*, motif—element filled with horizontal hatching; both the design structure and the motif have identical class 200 bifold rotational symmetry; *c*, adding dots to motif *b*, means that the figure can no longer be rotated 180° (as in *d*) and still remain the same design. The symmetry of the design featuring repetition of these units is translation (class 100). After Washburn 1977: fig. 12.

Symmetry may play a critical role in design structure, particularly with geometric or abstract motifs and configurations, but its analytical role has been fairly limited. The lack of agreement on notation, the cumbersome vocabulary, and the under-theorization of the transfer of symmetry patterns have hindered wider use of this approach. Some applications endeavored to make intersite comparisons more objective and systematic by using statistical procedures such as multidimensional scaling (Washburn and Matson 1985).

24.4 Style as Communication

Pottery styles can be defined, described, and analyzed from many different viewpoints, but the common underlying thread in these approaches is that style is a means of visual communication. Styles thus have social dimensions that link creators with observers. For archaeologists, the analytical problem becomes one of understanding what is being communicated, and to whom.

24.4.1 Information Theory

The information theory (or symbolic functionalist) approach to pottery decoration was a linchpin in the argument against the traditional dichotomy between style and function. As a medium of communication, styles have three major social functions (Wobst 1977: 327–28):

- Render interactions more predictable by providing immediate visual information about the participants.
- Reinforce societal differentiation by symbolizing group (rank, status) affiliation and enhancing within-group solidarity.
- Signify and maintain boundaries between groups through visual messages.

Symbolic functionalist analyses have pursued two closely related interpretations. One concerns the content or substance of the message (usually with reference to iconography); the other addresses the context or situation in which the message appears, which may be key to establishing why the message is sent at all. In addition, because the information content of styles can vary on different types of material objects—"the medium is the message"—it is important to consider how this messaging applies to pottery and pottery styles, especially in different contexts of use and visibility, and also how it relates to information communicated through other media (DeBoer 1991).

One social-communication function of pottery style is to send information about social, political, and economic group identity or affiliation. The need for such communication arises, in part, as societies grow larger and more internally differentiated. Stylistic messaging functions are served most fully as individuals and groups must convey information about themselves in interactions with others who may be physically or socially distant. Like items of clothing, headdresses, or insignia—today's rock band t-shirts, sports team caps, political bumper stickers—objects carried or displayed bear information about status or group affiliation that might otherwise be unknown or difficult to elicit. To be effective, artifacts bearing such coded stylistic messages should have high visibility in the contexts in which they are used, whether public or private, and the messages should be known and recognized by both the person(s) displaying the message and the person(s) intended to receive it (Bowser 2000; Weissner 1984). Recent study of the "complicated stamped" designs of Swift Creek (Southeastern US) pottery has led to recognition of the imagery—primarily

animals, especially birds—on these vessels and the carved wooden paddles used to finish them (fig. 9.1). It is also apparent that the same paddles were sometimes used on pots recovered in villages hundreds of kilometers apart (Wallis 2011, 2013; Wallis and O'Dell 2011; Williams and Elliott 1998). The designs likely were emblems ("totems") of identity of social groups, perhaps clans (Wallis 2006).

Styles may also play complex roles in boundary identification and maintenance (Hegmon 1998; Stark 1998). In the Baringo District of Kenya (Hodder 1977, 1979b, 1982), different categories of material culture—pottery, calabashes, clothing, ornaments, hairstyles, weapons—carry stylistic messages only when they call attention to boundaries and group identities. These are especially significant when tensions exist between groups (Hodder 1979b: 450). Tensions may be acute situational strains, as in warfare or conquest, or they may be institutionalized, as in the religion-based proscriptions about relations between males and females (see sexualized styles of clay furnaces for iron smelting: Childs 1988, 1989; Schmidt 2000). Among the Azande of southern Sudan, male and female activities are separated socially and physically. Pottery is made by men but owned and used by women, who cook food and serve it to men (Braithwaite 1982). These food transactions mark significant occasions of transcending or violating the social order, as male-female category boundaries must be publicly crossed. The decoration on serving vessels acts as a ritual marker or message acknowledging the symbolic ambiguity engendered by this breach of the accepted social order. Men's drinking cups, however, do not publicly pass between men's and women's hands and are left undecorated as are the chief's eating utensils, because the chief eats alone.

The production of identical pottery styles in three contiguous Hopi and Hopi-Tewa Pueblo communities (Stanislawski 1978) suggests that there, pottery is not important in symbolizing or sending messages about group identities; such affiliations and boundaries are asserted through other kinds of behavior. The same may hold true for the Shipibo-Conibo rim designs (DeBoer and Moore 1982).

24.4.2 Active or Passive?

Although the style-function dichotomy is now largely rejected, the binary that continues to provoke debate is the degree to which, and in what situations, styles' communication and information-sharing roles are active or passive. In the early days of interaction-theory analysis, one approach to design elements sought unconscious selection: elements were considered "the smallest units or elements of design that would be non-consciously selected [by the potter] based upon learning patterns" (Longacre 1964: 163). Another definition attempted to identify conscious choices: elements result "from a choice on the part of the manufacturer from a number of possibilities, made to produce a certain effect" (Deetz 1965: 46).

These differences stimulated a long-running dispute about the source and intent of the information or messages coded into a decorative style and its elements (Hegmon 1992: 522–24), a debate reminiscent in some ways of those about pottery classification and whether types are inherent (emic) or created (etic). A major protagonist in this disagreement, James Sackett (1977b, 1982, 1985, 1986) maintained that styles could be active or passive, and most stylistic behavior was the latter. Styles were typically based on "isochrestic" choices: unconscious (passive) selection from among equivalent alternatives learned as part of participation in a social group, which may inform the archaeologist about ethnicity. Polly Weissner (1983, 1984, 1985), in contrast, viewed styles as active, and choices of elements (or other features) represented conscious decisions relating different kinds of information. Her approach, which Sackett termed "iconological," distinguished between "emblemic" style (related to groups and boundaries) and "assertive" style (personal and individualized). Despite their disagreements, both Sackett and Weissner accepted that multiple kinds of styles exist. A particularly important outcome of recent approaches to stylistic analyses of material culture in general is that styles and their creation are now accorded active (intentional, direct) rather than solely passive roles (Carr 1995: table 7–4; Hegmon 1992; Pryor and Carr 1995: table 8–1).

24.4.3 Learning/Transmission

Another outgrowth—or product of continual remodeling—of earlier approaches to style, such as the interaction hypothesis, is a refocus on learning. A search for better understanding of how pottery-making knowledge was passed along, the "weak link" in the chain of inferences about style (Skibo 2013: 67), was the original basis for long-term ethnoarchaeological research among the Kalinga.

Early interaction studies assumed that potters were all female and learned techniques of manufacture and decoration intergenerationally from their mothers (Bunzel 1972: 54)—that is, vertical transmission. But closer examination of cross-cultural teaching-learning patterns and sources of inspiration for decoration quickly revealed that these phenomena are more complex than originally expected, and knowledge may be transmitted horizontally through nonrelatives and other groups (Hayden and Cannon 1984: 330–41; Herbich 1987; Lathrap 1983; Roe 1980; Stanislawski 1978: 219; Stanislawski and Stanislawski 1978: 66–73).

More recent intensive investigations of learning strategies, patterns of knowledge transfer, and vectors of cultural transmission of material technologies are contributing insight into the tangled sources of stylistic variation in material culture in general (see, e.g., Bowser and Patton 2008; Eerkens and Lipo 2005, 2007; Finlay and Bamforth 2008; Gosselain 2011; Pryor and Carr 1995; Stark et al. 2008a, 2008b). One approach borrows the concepts of "communities of practice" and "situated learning," popular in the business literature (Lave and Wenger 1991; Wenger and Snyder 2000), into studies

of transmission of pottery knowledge. A study of early pottery production in the Southeastern United States returns to concerns about postmarital residence, concluding —in part on the basis of handedness evident in punctated decoration—that marriage alliances among exogamous matrilocal groups enabled ongoing contacts among potters in multiple communities of practice (Sassaman and Rudolphi 2001).

24.4.4 Visibility

Pottery styles may vary depending on the nature of the intended audience and on how the vessels are meant to be used or displayed. The presence and context of messages may differ in private versus public contexts (Hegmon 1992: 521). The activity vs. passivity of styles has been stereotypically gendered with respect to male/public/active versus female/domestic/passive contexts of usage. Pottery's portability is an advantage in messaging in transitions from familiar-to-unfamiliar or sacred-to-profane contexts or in situations of changing visibility.

Clay pots serve in mundane tasks, such as domestic cooking and storage or as chamber pots, where their existence goes virtually unremarked. Pottery's household display functions may be passive, seemingly simply for adornment and testifying to the skill of the potter (Balfet 1965: 163). In the Ecuadorian Amazon, on the other hand, the painted decoration in domestic pottery may take a more active role in communicating the potter's—a woman's—political (but not ethnic) affiliation (Bowser 2000). In north Cameroon, pottery decoration represents communication with supernaturals in private usage, rather than sending messages to other individuals or groups (Sterner 1989). Style, then, plays a role in negotiating social, political, and religious identities, particularly in small scale societies, not only vis-à-vis others but also with "socially *close* people *within* groups" to signify shared alliance and beliefs (Bowser 2000: 242, emphasis in original).

In public contexts, pottery may have high visibility. Settings may be culturally significant or emotionally charged, such as religious ceremonies, mortuary ritual, and feasts or other community activity involving food. An analysis of 178 vessels from five Shipibo-Conibo (Peru) settlements revealed that vessels used in public, especially on festive occasions, exhibited relatively high stylistic diversity, while those used within household compounds exhibited low diversity in their border designs (DeBoer and Moore 1982). The rim decoration on public vessels thus did not seem to symbolize compound identity, but instead was a message of ostentatious display. This did not match the expectation that clear stylistic messages would be sent across boundaries by means of greater consistency (less diversity) in publicly used vessels. The authors note that the larger and more visible designs on the bodies of vessels may behave differently and fulfill expectations; the alternative is that rim designs are not intended to convey messages in such feasting situations.

Two studies of highly visible American Southwest pottery, Salado polychrome (Crown 1994) and early Pueblo material (Hegmon 1995), thoroughly explore pottery styles, exemplifying many of the approaches reviewed here and contextualizing them in reference to technology and use.

24.4.5 Meaning

Some new approaches to pottery embellishment have focused on content and meaning, rather than descriptive characterization of a style or how it is created. Part of the communication function of decoration of pottery is iconographic: certain motifs are painted or incised because they represent supernaturals or are widely recognized symbols of concepts and beliefs (Knight 2013). Iconography is about icons: images or representations and their referents. Their "meanings" are likely to be empirical or culture-specific and may relate to the specific uses of the vessels. Thus the meanings of styles and images may be multilayered, revealing a continuum of complexity in transmission of messages interpretable on several levels. At all these levels and layers, it is worth asking, Whose meaning? The creator's intended meaning? The viewers' inferences of meanings? Does the one always map the other?

In discussing the meanings of styles and their iconography, it is important to recall the caution suggested in ethnoarchaeological studies about the differences between what informants say they do and what they actually do. Informants may ascribe a particular meaning to an element or motif or acknowledge a significant role of a particular color or structure or number in their belief system, but this admission does not ensure an unvarying association in the decorative system. Among the Zuni, for example, the number four is prominent in literary and ceremonial traditions, and potters expressed a preference for four designs on their painted vessels (Bunzel 1972: 20–23). Nonetheless, in actual execution three seemed to be the most common number of repetitions of a design (or divisions of the design space). In pottery decoration as in other aspects of culture, there may be wide disparities between the ideal and the reality of behavior.

24.5 Further Developments

Additional trends have gained momentum in archaeological style analysis in general and pottery style specifically. Some of these are still "ceramic sociological" in emphasis, whereas others address broader concerns. For example, greater attention has been paid to the relations between decoration and vessel form. Ethnoarchaeological studies showed that potters explicitly associate specific design motifs and arrangements with particular shapes (Friedrich 1970: 335; Stanislawski 1978: 215), relations also noted in the archaeological record (LeBlanc and Watson 1973; Plog 1980: 112–13).

Most analyses of pottery decoration and decorative styles have been devoted to painted pottery, but few address the significance of color per se as opposed to texture or form (see Cecil and Neff 2006; Helms 1993; Sahlins 1976). Analyses of Pueblo black-on-white painted pottery have indicated that black hachure was a convention for representing the color turquoise (Plog 2003). Occasionally the decoration on pots was obliterated and painted over, and the vessels were refired in a kind of ritual renewal (Crown and Wills 2003).

24.5.1 Theoretical Contexts

Other developments draw heavily from broader developments in anthropology/archaeology method and theory. For example, the use of agency and practice theories represents contributions of post-processual approaches, encouraging emphases such as gender, identity, embodiment, and the role of the individual (e.g, Lesure 2005; Pauketat 2001). Some scholars have sought to bridge the style-function, active-passive, structure-agency dichotomies with reference to practice theory and the *habitus* concept (Bourdieu 1990; see Dietler and Herbich 1998). In one study of Southwest painted pottery design, painting is considered to represent individual agency within the overall structuring provided by a style tradition (Hegmon and Kulow 2005). Styles are the product of actors' day-to-day practice, including their entire corpus of choices and decisions, within the structural constraints of societal institutions.

Growing attention to materiality and technology in anthropology prompted increased interest in the notion of technological styles (Lechtman 1977, 1984). Technological styles encompass variables of raw material or medium as well as processes of manufacture and execution: the objects represent "ways of doing" as well as exemplars of individual performance and skill. The significance of decorative elements and motifs and their arrangements includes the chemical compositions of the pigments and the tools with which they are made. Technological-style approaches frequently accompany increased application of technological choice models (Lemonnier 1986, 1992, 1993) and the function of styles can be considered within general considerations of overall vessel "performance" (Skibo 2013: 15).

24.5.2 Style Change

Four barriers may prevent precise replication of designs, or act as sources of decorative variability (Hardin 1984: 592–600): communication differentials (lack of visual access), decoding differentials (idiosyncratic analysis of design), stylistic screens (modification and reinterpretation), and style boundaries (change through time). The variable roles of information transfer give rise to additional problems in interpreting social interaction as measured by the stability or borrowing of motifs and symmetry patterns. Certain aspects of style—colors, structures, symmetry relations—may be more or less entangled in the message and information exchange functions and therefore more or less likely to alter in differing circumstances of interaction between pottery producers.

These barriers may play a role in what are perhaps the most intractable questions about style in archaeology: the causes and rates of stylistic change. Stylistic change is likely to vary with period and age, and to fluctuate and suffer lags as a consequence of social and geographic distance. Reconstructing stylistic change from the archaeological record will be hindered if different kinds of decoration characterize different sizes of pots and if these are replaced at different rates (Graves 1985; Linares de Sapir 1969: 9). Similarly, it is important to distinguish whether styles and motifs are changing or expanding in popularity as opposed to the movement of actual pots bearing the decoration. On a particularistic level, the size of the social networks and the intensity of the artistic communication between practitioners are likely to be involved (see Friedrich 1970: 342; Lathrap 1983: 39). Structurally, a look at stylistic change through time in medieval Nubia (Adams 1979) called attention to the lack of clear evidence for change in pottery produced and used during periods of dramatic cultural transformations. This is a sobering observation in light of traditional archaeological practices that infer social changes through periodizations of sites and regions based on disjunctions in ceramic styles and forms.

Productive contributions to an understanding of stylistic change may arise from evolutionary approaches. In their view of style-function concerns, archaeologists favoring selectionism suggest that variation is functional if it responds to selection pressures, but stylistic if it occurs through “neutral innovation” or “random drift” (Neiman 1995; Shennan and Wilkinson 2001). Thus designs may have different adaptive significance and the more strongly adaptive (or functional) the design the more slowly it will change (Graves 1981: 307–8).

24.5.3 In Sum . . .

Pottery styles and stylistic analyses are complex, and there are no simple ways to interpret them. Distinct motifs and elements may be associated with specific vessel forms used in different activities. Pottery decoration may transmit important messages in some societies but not in others. Messages may differ in public versus private contexts.

Pottery may symbolize affiliation and maintain boundaries . . . or it may not. The information content of pottery styles may differ and function differently in ancient states and civilizations as compared with today's globalized world.

Despite efforts to reconcile the interaction and information exchange theories (Hill 1985), the style versus function debates, and the passive versus active dilemma, methodological and interpretive problems still exist with the various approaches. One set of methodological problems resides in the assumptions that accompany stylistic analysis as well as many other kinds of analyses of archaeological materials. Some of these assumptions are based on statistical models and involve questions of sample size, randomness, independence, and level of measurement. Still others concern the formation of the archaeological record, including the use and discard of pottery and processes that alter the condition of an activity area between ancient times and archaeological excavation. Difficulties are magnified exponentially by the difficulty of inferring nonmaterial culture—social relations, meanings, behavior—from fragmentary material remains.

Stylistic analyses have applied different methods to different media, using objects with different kinds of styles and different levels of participation in social, political, and economic institutions, and from societies ancient and modern with different levels of complexity. Small wonder, then, given so many variables, that styles seem to behave unpredictably for inferential purposes. Ultimately, the interpretive uncertainties and unresolved questions about stylistic analyses of archaeological pottery spring from incomplete and contested understandings of the nature of styles in general: what they are (definition), what they do (function), how they are learned and transmitted (technology transfer), how they are produced (innovative agency versus tradition), and how they change.

Minimally, it is evident from the past half century of studying pottery styles that styles have technologies, technologies have styles, and both styles and technologies have functions. A pottery style is a visual expression, unique to a given place-time setting, which may transmit, to varying degrees, information about the society that produced the style, about the producer(s), and about the specific context or location in which the pottery appears.

The conceptual components of general pottery Style-with-a-capital-S can be graphically modeled, starting with an equilateral triangle or ternary diagram (fig. 24.9), its three vertices labeled A: style, B: technology, and C: function. Here, "A: style" refers to the aesthetics of visual quality and formal characteristics of a Style, along with descriptors such as representational, realistic, geometric, and so on. "B: technology" refers to "way of doing" agentive aspects such as performance and production involved in creating works in a given Style. "C: function" refers to the meaning and information content of a Style. The A-B line or edge presents a continuum between the dimensions of skill and techniques respectively; the A-C edge is the content dimension of a Style, a

continuum from symbolism/iconology to meaning/information respectively; and the C-B function-technology continuum represents context of use or display to material/medium.

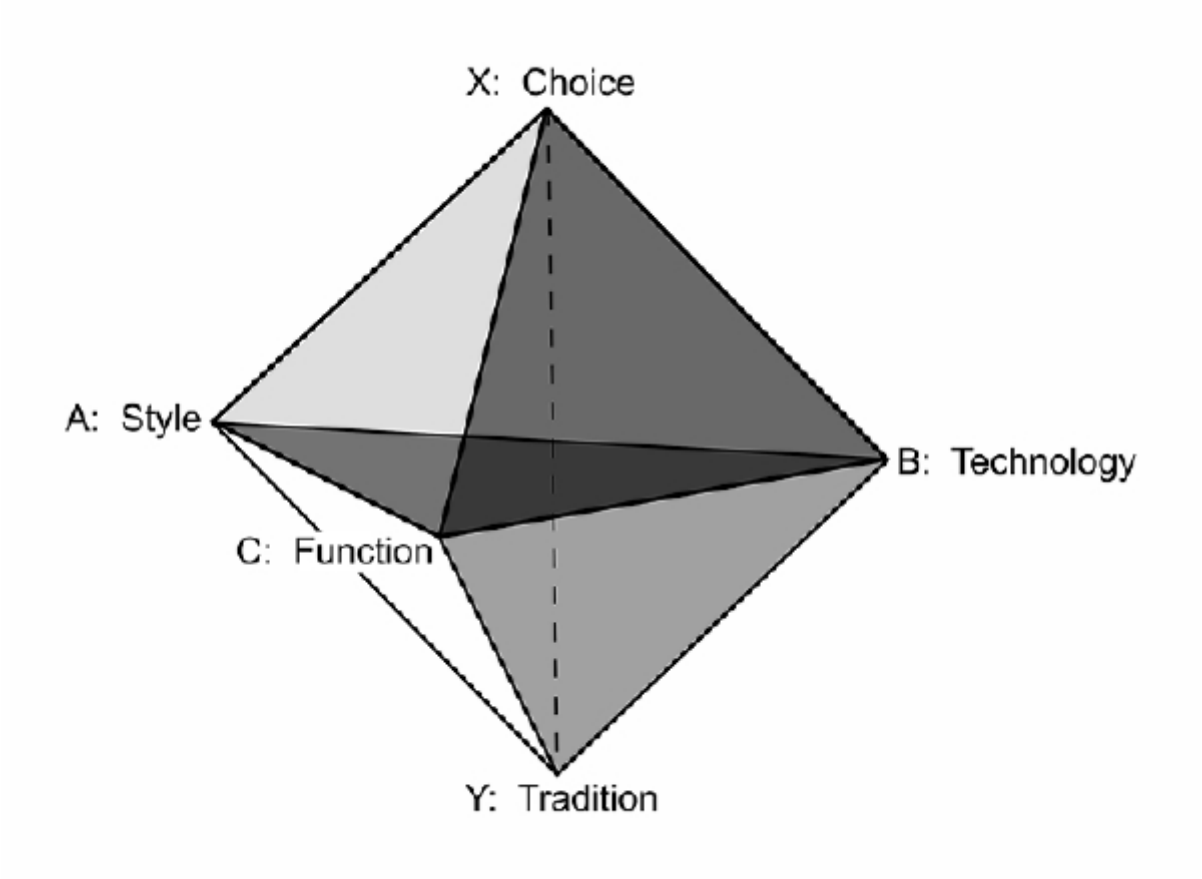

Figure 24.9 A three-dimensional, triangular bi-pyramidal model of the dimensions of pottery style. The core of the solid, the ABC plane, combines the aesthetic qualities of style (A) with the "way of doing" technology component (B) and the communication function (C). The vertical dimension, XY, is the continuum between individual choice/agency and tradition/constraints. See text for further explanation.

This triangle can be envisioned in a horizontal plane and transformed into a three-dimensional solid, a tetrahedron or three-sided pyramid; two of these can be put together, upper and lower, by sharing the ABC plane. X, the vertex of the upper pyramid, is represented by choice/agency, which is played out in all parts of style, function, and technology, and allows for active, individual decision-making, variation, and creativity in the decorating of a pot. Y, the vertex of the lower tetrahedron, represents the more passive or unconscious role of *habitus*, tradition, custom, and "isochrestic variation" or structure that constrains variation within cultural norms or standards.

The five vertices of the solid represent the major analytical approaches and descriptive dimensions archaeologists bring to bear in studying pottery styles. The three extended vertical edges that join X to Y through vertices A, B, and C, indicate that these three components of Style may vary in the degree to which individual freedoms/choices or customs/cultural standards dominate their expression. Most analytical approaches to

actual, empirical pottery styles—essentially the elusive “middle-range theories”—and the styles themselves can be conceptually accommodated somewhere within the space of this “triangular bi-pyramidal” solid.

25 Functions and Forms

> If the Kalinga ranked their material possessions in terms of their level of importance, pottery would be near the bottom of the list.
>
> Skibo 2009: 35

Objects fashioned of clay have served varied human needs for thousands of years, from sewer pipe to spacecraft insulation, but the broadest use of clay has been in containers—pottery vessels. In their role as containers, ceramic vessels are tools (Braun 1983) and a subset of a much broader category of utilitarian devices called facilities (Wagner 1960; see also Lustig-Arecco 1975; Oswalt 1973). Facilities hold or restrain the movement of their contents and include such diverse things as corrals, granaries, and baskets. Facilities are not necessarily passive containers; they may increase the usefulness of their contents by prolonging their life span or by allowing them to be transformed by different kinds of energy. With the background provided by characterization of ceramics' physical, mechanical, and thermal properties (chaps. 18 and 19), it is possible to develop a fuller picture of pottery functions and the factors that contribute to the ability of a container to serve those functions satisfactorily.

A multitude of approaches, direct and indirect, permit assessments of the uses of the ceramics recovered in archaeological excavations (see Skibo 2013). This chapter reviews methods for investigating the use-related functions of pottery containers in primarily domestic contexts. Many other kinds of clay containers are excluded, such as burial urns, flower vases, chamber pots, cache vessels, oil lamps, and other special-use containers with quasi-industrial or manufacturing roles, for example in salt-making (Charlton 1969; Muller 1987), dairying (Craig et al. 2005; Dunne et al. 2012), metallurgy (e.g., *tuyères*, crucibles: Martinón-Torres and Rehren 2009), or molds; along with noncontainers such as pottery toys, candlesticks, figurines, smoking pipes, primary and secondary tools for tasks such as spinning, and construction materials (tiles, bricks). Some containers would have had technological or morphological requirements similar to those of domestic pots, if, for example, they were used with or over a fire or to contain liquids.

Although ceramics have served nonculinary purposes for thousands of years, it is in domestic and culinary roles that their functions as containers can be addressed most broadly and comparatively through time—that of the vessels' use-lives as well as "archaeological time"—and over a wide geographical area. In these activities the full spectrum of cultural and technological factors underlying the choices involved in manufacturing a vessel is brought into play. One can easily make functional inferences from the ceramic properties, with only a small shift of analytical perspective from domestic to nondomestic arenas.

25.1 Vessel Form, Technology, and Use

Compared with containers of perishable materials, such as baskets, gourds, and bags of net or skin, fired clay vessels can accommodate far more varied functions and have longer and far more varied use-lives. For storage purposes, fired clay pots are longer lasting and more durable, resistant to destruction by rodents or insects as well as moisture, and suitable for holding liquids, and they can be sealed against vermin. In processing activities such as mixing, soaking, and grinding as well as in domestic and industrial activities involving heat, pots can retain liquids, they can be set directly into a fire, and their rigidity allows them to withstand agitation of the contents without damage or deformation. The main disadvantage of pottery is its brittleness or low resistance to mechanical stress: pots are easily broken if dropped or dealt an accidental blow.

Pottery containers come in all shapes and sizes, and each food item or occasion of preparation may have its own vessel or set of vessels in a well-equipped household. Ethnographically, determining the functions of these vessels is a relatively simple matter of asking questions and recording observations: This vessel is used for boiling beans, that one for carrying water, this for drinking, that for storing grain, and those for community beer-making festivities, boiling rice, toasting manioc cakes, simmering sauces, grinding condiments, making offerings to the ancestors, and so forth. Each kind of use places different demands on the vessel, and its suitability for a particular task depends on its design, in an engineering as well as an aesthetic sense.

The use-functions of ceramic containers lie in three broad realms: storage, processing (or transformation), and transfer or transport. These can be parsed into more specific kinds of activities, each of which favors different design emphases: different combinations of attributes of composition and form to meet the particular demands of its use. Will the contents be liquid or dry? Hot or cold? What is the anticipated volume or capacity? How, and how frequently, will the contents be accessed—with a hand or a scooping tool, or by pouring? Will the activity or function be tended (watched, manipulated) or unattended? Figure 25.1 diagrams these considerations in the three main categories of pottery use—storage, processing, and transfer.

The complex relations among use, morphology, and technology of pottery vessels began to be closely investigated in the early 1980s (e.g., Henrickson and McDonald 1983; Howard 1981: table 1.1; Smith 1983, 1985). Of eighteen proposed form/function relationships examined using ethnographic samples from the American Southwest and West Africa, ten were supported in the literature (Smith 1983: table 42). The findings include the following points:

- Vessels used for both cooking and processing have larger orifices than those used for storage, but duration of storage has no effect on orifice diameter.
- Pots for long-term storage have greater volumes than those for short-term storage.
- Vessels for transporting liquids have smaller orifices than those used for other purposes.
- Pots used in transport over small distances have greater volumes than those carried over large distances.

· Cooking and heating pots have greater volumes than those used for eating.
· Serving and eating utensils tend to have their greatest diameter at the rim (unrestricted forms).

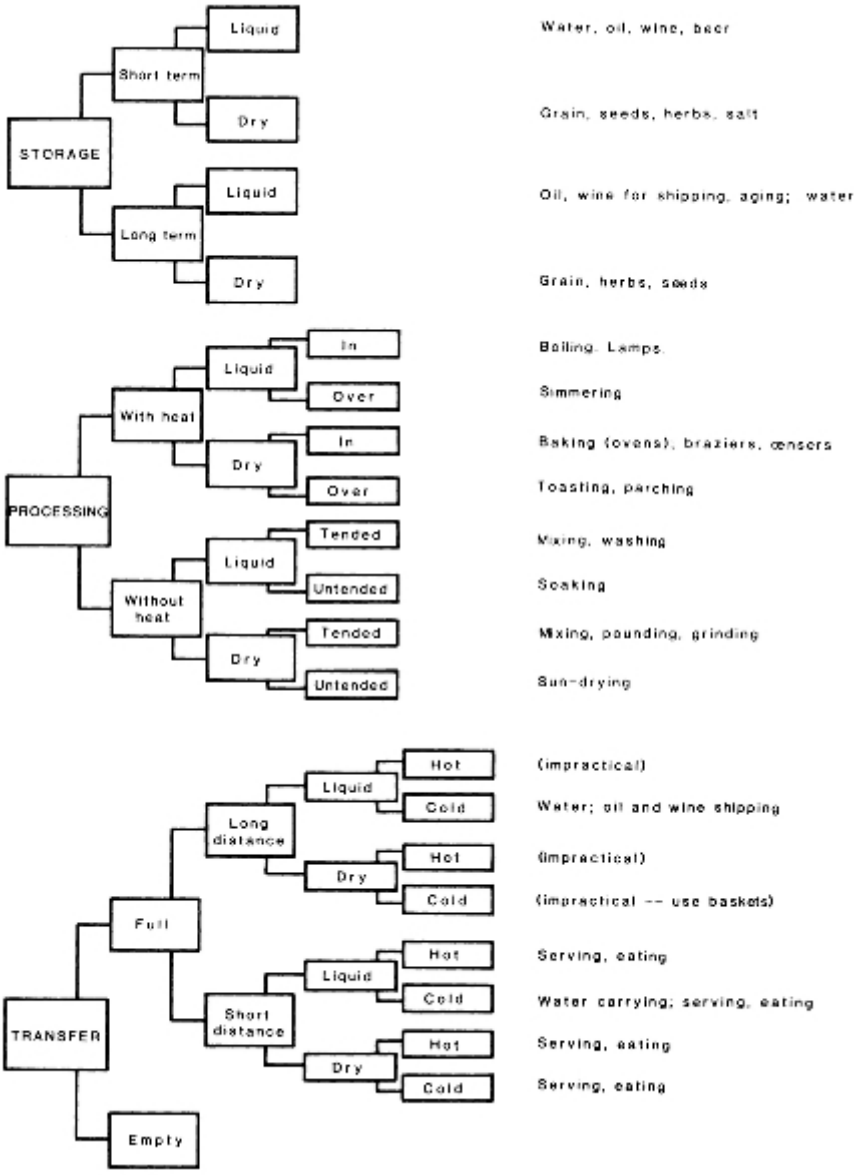

Figure 25.1 Categories of vessel use.

Other predicted relationships were equivocal, however (Henrickson and McDonald 1983: 632–34; Miller 1985: 60–62; Plog 1980: 86–87; Smith 1983: 221).

Proposed relations between variables of form and use were based on assumptions about intended function of the vessels and sometimes were not matched by actual usage. These differences occur for many reasons. Ceramic attributes relate to several behavior complexes, including scale of manufacture. Pots are multifunctional: vessels may have multiple uses, the same vessel being employed to both carry water and store it, or to prepare food and eat it. They can be recycled into secondary uses after age or accident limits their ability to perform their primary or intended function. Empirically observed deviations from a predicted ideal will occur because these relations refer to general

shapes and uses (cooking, storing), whereas uses with specific contents (cooking beans, storing wine) may place more constraints on variability (e.g., in secondary form characteristics: spouts, handles, etc.). In terms of a ceramic assemblage, forms may exhibit a great deal of redundancy and a lack of secondary attributes that aid in efficient performance of their intended tasks or as clues to their intended or actual function (Miller 1985: 62–67). Thus, a pottery container's primary use-related variables—shape, size, function, composition—are interdependent and their relations are ones of multivariate causality. One-to-one correlations among these variables are rare to nonexistent, and no single attribute set perfectly predicts another.

A pottery vessel is, ultimately, a product of a set of decisions about composition, shape, and use that are not necessarily equally weighted, do not always adhere to the principles of modern materials science, and are likely heavily influenced by intangibles such as tradition and custom. Container design must accommodate the sometimes conflicting needs and demands of multiple uses (and resource constraints). Design may represent a compromise to meet varied needs adequately, rather than to serve a single purpose optimally. Over-determinacy is a particular danger in explorations of the relations between use and form, so care must be taken not to over-rationalize the decisions potters made in designing their products. Notwithstanding these cautions, the relations of form, function, and technology may be summarized in a simplified, idealized way (table 25.1).

Table 25.1 Predicted Archaeological Correlates of Vessel Function

Functional Category	Shape	Material	Surface Treatment and Decoration	Depositional Context	Frequency	Clues
Storage vessels	Restricted forms, orifice modified for pouring or closure; appendages for suspension or movement (tipping)	Variable (possible concern for low porosity)	Variable for display or messages; slip or glaze to reduce permeability	Dwellings (sometimes set into ground); trash middens	Low (low replacement); may be reuse of broken or old vessels	Residues of stored goods in pores
Cooking pots	Rounded, conical, globular, unrestricted; generally lacking angles	Coarse and porous, thin walls, thermal shock resistant	Little to none; surface roughening for handling ease	Dwellings, trash middens; rarely in special deposits (e.g., burials)	High (frequent replacement)	Patterns of exterior sooting or blackening; burned contents
Food preparation (without heat)	Unrestricted forms, simple shapes	Emphasis on mechanical strength; relatively coarse, dense	Variable; generally low	Dwellings, trash middens	Moderate?	Internal wear; abrasion or pitting
Serving	Unrestricted for easy access; often with handles; flat bases or supports for stability	May be fine	Generally high, for display or symbolic roles	Dwellings, trash middens, special deposits (burials, caches)	High (frequent use and replacement)	Sizes correspond to individual servings or group size
Transport	Convenient for stacking; handles; lightweight; restricted orifice	Emphasis on mechanical strength; dense, hard	Variable, generally low; slip or glaze to reduce permeability	Trash middens, nondomestic (market) areas	Variable	Uniform size or multiple units of size; residues of contents

Source: After Howard 1981: table 1.1.

25.2 Indirect Evidence and Inferred Functions

Archaeologists can bring to bear many kinds of indirect evidence, traditional and nontraditional, in trying to understand the functions of pottery vessels. It is important to recognize the difference between direct and indirect evidence, the latter contributing to inferences of function or "inferred use" (table 25.2). Indirect evidence and inferred uses do not discriminate intended or actual uses, re-use, or information about contents. A traditional basis for inferring the function of any artifact is its context of recovery. A bowl holding jade beads found under a Maya stela, a jar filled with seeds in a Southwestern pueblo ruin, smashed effigies beneath the east side of a Florida burial mound—these give clear indications of use of the vessel, at least at the point in its life history that it was removed from "systemic context" and entered "archaeological context" (Schiffer 1976). Vessels typically have multiple uses during their life spans, however, so that their archaeological context is merely their final resting place rather than an accurate indicator of how their use-life was spent. For example, one may ask whether a vessel was manufactured specifically for a sub-stela cache: Was that both its intended function and its sole function from the start of its existence? Or were these vessels used in other activities before being placed in these special deposits (see Bray 1982)? Recovery context and information about it are dependent on the strategies employed in excavating a site rather than the skills of the ceramic analyst, however, and are not further treated here.

Other approaches to ascertaining vessel function are based to a variable extent on analogies drawn from ethnography and particularly ethnoarchaeology and experimental archaeology (Skibo 2013). These and other studies have investigated vessel form; physical attributes of composition, thickness, and surface treatment; and the clusters of attributes relating to resistance to mechanical and physical stresses, porosity/permeability, and thermal behavior.

Table 25.2 Evidence of Function in Archaeological Pottery

	INDIRECT EVIDENCE Yields "inferred use" (cannot distinguish intended, actual, reuse, or contents); largely based on analogical reasoning	DIRECT EVIDENCE May be multiple uses, and not all may leave evidence
USES Includes Storage (short- or long-term) Processing (with or without heat); tended or untended Transfer (full or empty; short- or long-distance)	Recovery context Ethnographic analogy Historical accounts; ethnotaxonomy Experimentation, replication Surface treatment: texturing Morphology: —Dimensions, proportions —Attachments (secondary form char.) —Properties (capacity, stability,weight, accessibility) Technological, mechanical properties (relates to experimentation, ceramic engineering, morphology) —Paste composition —Thickness —Remnant (residual) properties: hardness/strength; resistance to thermal and mechanical stress; permeability and porosity	Recovery context: gives final use (e.g., mortuary, storage room, firepit, construction fill) or discard (midden) Written/historical records (may give intended, actual, or final use) Surface characteristics: —Damage (abrasion, attrition, pitting) —Fireclouds, sooting, charring
CONTENTS Liquid or dry Hot or cold	Residues, crusts, sooting Inferred from "inferred use"	Written/historical records (intended or actual use) Context of recovery with contents (actual use) Surface and pore residues (actual contents)

25.2.1 Physical Attributes

All use-related properties are influenced by the potter's choices and decisions during the manufacturing process (see Skibo 2013: 39–45) and so to some degree they are all manipulable. Thus before a vessel is even shaped, the design of a durable and appropriate container for a given function originates with the selection and manipulation of raw materials. The potter's most fundamental decision is which clay to use, and whether and how to modify it. Both decisions may be constrained (if not determined) by

proximity and custom rather than completely free will. Because there may be a scarcity of clays suited to special purposes, such as refractory clays to withstand high temperatures, subsequent decisions—about temper, thickness, and so forth—can be seen as strategies that modify the raw clay material toward the pragmatic goal of creating a useful container. The use of different clays and tempers for different form or function classes of pottery is widely known ethnographically (Arnold 1978: 367; DeBoer and Lathrap 1979: 116; Gosselain 1994; Stone 1950: 270; cf. Rye and Evans 1976: 126–27). Thus the chemistry, mineralogy, granulometry, and proportions of clays and inclusions establish one baseline for variability in the use-related properties of any ceramic. These compositional attributes may be modified throughout the manufacturing process by the potter's skill in preparing the clay.

The shape and size of vessels may be heavily dependent on the properties of the clay used for them, as it was in Sardinia: when one customary clay source was exhausted, potters had to move closer to another source of clay that was of inferior quality, and large vessels either could no longer be made or had to be reduced in size (Annis 1985: 253). The thickness of the vessel walls is related, in part, to the size of the container and its intended use, as well as to the skill of the potter. In general, larger vessels require thicker walls for structural support, which often necessitates more temper to reinforce the clay. The intended appearance and use of the vessel may dictate that some areas be thickened to enhance their strength in use, for example, at the rim or where handles are attached.

Thickness also depends on the properties of the clay and inclusions being used. During the shaping of the wet clay, the walls serve as a structural support: like the walls of a house, they rest upon a foundation (the base) and support a heavy superstructure—shoulder, neck, collar, rim, flanges, handles, spouts, and so forth. Because this superstructure is also composed of wet, heavy clay, the vessel may slump or warp during drying if the walls and foundation are not sufficiently strong—that is, they do not develop enough green strength—for support.

Relations between composition and thickness can be illustrated by the *tinajas,* or water-carrying jars produced in Chinautla, highland Guatemala. The clay contains diatoms and the temper is a pumiceous volcanic ash (Rice 1976a); both of these siliceous inclusions, by their lightness and angularity, permitted the manufacture of jars long held in great esteem for their thin walls, light weight, and durability (Arnold et al. 1978).

Surface treatments can affect the use-related properties of a ceramic, particularly its permeability. These modifications may be applied to the interior or exterior surface of the vessel, or both, either before or after firing. Burnishing compacts and smooths the surface, creating a thin, dense layer of fine particles that increases resistance to abrasion and attrition, and also may reduce permeability to some degree (Birmingham 1975; Henrickson and McDonald 1983: 633).

Overall coatings decrease or eliminate permeability by acting as a barrier to penetration of liquids. Glazes are the most obvious example, but in times and areas of the world where glazes were not used by traditional potters (e.g., much of the Western Hemisphere), applying a slip may decrease permeability. Glazes, and possibly slips, may be harder, more resilient, and more resistant to abrasion than the clay body. Postfiring coatings, attested ethnographically, are interior or exterior applications of an organic substance to a vessel before its use in cooking or storing liquids.

Surface roughening treatments are important for transfer functions: a rough surface provides a more secure grip. The classic illustration is a slipped water jar: heavy and wet, it is slippery and difficult to grasp. Textured surfaces, however, increase the friction, making it less slippery and more easily lifted and carried (Boulanger and Hudson 2012). A number of procedures can be used: striated or combed surfaces are common on large jars from prehistoric Mesoamerica; in the eastern United States various kinds of impressing and stamping are known—cord, net, corncob, checked, complicated, and so forth; in the Southwestern United States "corrugated" surfaces may serve the same function.

25.2.2 Forms and Functions

Relations between the form of a vessel and its functions are of long-standing interest and are usually the conceptual starting point for analyzing function (see Skibo 2013: 28–36). Just as a chipped stone tool with a point and a long sharp edge will be called a knife by analogy to the shape and usage of modern knives, so a low, open ceramic vessel will be called a bowl by analogy with the shapes of bowls in modern kitchens. The application of familiar or generic shape terms such as bowl and jar tends to ascribe a particular function without clear indications that such was the vessel's intended or actual use, however (sec. 13.4.3). Many such terms—storage jar, cooking pot, serving bowl—reinforce the subjective association of form and function: each of these binomials combines a use category with a shape category. The differences between this bowl and another vessel that by the same principles might be categorized as a jar are not always well understood and are often contradictory. In addition, many complex vessel shapes defy labeling by these familiar terms.

Despite the dangers of overestimating causal relations between form and function, it is possible to suggest advantages and disadvantages, or inducements and constraints, which may have been factors in design decisions (see Braun 1980; Ericson et al. 1972; Hally 1986; Smith 1983). The most important portions of a vessel that relate to its functions are its orifice, its base, and secondary components such as handles, feet, spouts, and flanges or ridges (see box 13.2). The major use-related properties of ceramic containers directly related to form or shape include accessibility of the contents, capacity, stability, and transportability or ease of movement. Several other, more specific properties bear on use as well.

The orifice or mouth of the vessel is the area most specifically modified or adapted to distinct uses, and the use-related property it most directly affects is accessibility of the contents. Particularly significant attributes include the restrictedness of the orifice, the presence/absence of a neck or collar, and the rim and lip form. An unrestricted orifice facilitates moving contents into and out of a vessel, and allows easy entry to the contents by the hand or a utensil for mixing or stirring. This accessibility makes such vessels suitable for holding items that will be used frequently or temporarily. The open mouth also reveals the contents, which might be important in serving from a dish or plate. A sharply restricted orifice, on the other hand, constrains access to the contents and may indicate infrequent usage. It is particularly helpful for keeping the contents, especially liquids, inside and can prevent spills during serving and processing. In cooking pots a restricted orifice retards evaporation of a liquid during prolonged heating; in storage vessels, it can be easily closed with a lid or stopper.

A neck or collar is an adaptation of the orifice, particularly a restricted orifice, for certain uses. Water jars, for example, typically have narrow necks to inhibit the liquid from spilling during movement. A tall, flaring neck acts much like a spout for control while pouring the contents out, and as a funnel during filling. A wide-necked vessel may be more appropriate for storing goods that are sometimes poured out and sometimes scooped out. It is not the diameter of the mouth opening itself, but rather the diameter at the maximum constriction of the neck—the throat—that determines the accessibility of the contents.

Rims and lips are other areas of orifice modification with functional significance, whether on a restricted or unrestricted, necked or neckless, vessel. Because the mouth of a container is most directly involved with entry to the contents, thickening the rim or lip with a bolster or flange strengthens it against breakage and facilitates lifting and pouring. Lip and rim modifications also may make it easier to close the vessel: an interior ridge, for example, is a resting place—a lid seat—for a cover, while an exterior lip bolster or ridge allows a cloth or skin cover to be tied below, enhancing the storage function.

The capacity or volume of a vessel depends upon its shape and size. The relations between use and capacity of a vessel involve the amount and kind of material (liquid or dry) the vessel contains, the length of time it is to be held, the number of anticipated users of the contents during that time (Nelson 1981: 109–11), and microenvironmental factors such as availability of water or other necessities (see Arnold 1985: 145–47). If entire vessels are available, their capacities can be determined directly by filling with a liquid (water) or dry substance (grains) and then removing and measuring the volume of the contents. Otherwise, capacity can be calculated directly from several common measurements (see table 13.1; also Rodriguez and Hastorf 2013) and expressed in volumetric units such as cubic centimeters (cc), cups, liters, or gallons (one liter is 1000 cc; one cup is roughly 240 cc/mL). Vessels may be made in sizes that suggest

indigenous standard units of capacity or multiples of such units (e.g., Rottländer 1967; Turner and Lofgren 1966).

The stability of a vessel refers to its resistance to tipping and is determined by overall shape, proportion, base, and center of gravity. The center of gravity is the point of balance of the vessel and is a function of mass, shape, and weight. Vessels that are taller than they are broad, such as tall, narrow cylinders, or that have a high shoulder (fig. 13.6*g*) or unusually high and heavy necks or collars (e.g., fig. 1.1), have a high center of gravity. They are unstable—a vessel is in stable equilibrium if its center of gravity must be raised to tip it (Shepard 1976: 238)—and require some sort of stand or support, or partial burial, to remain upright. Although instability might appear to be undesirable, it may be advantageous in certain situations such as tilting a vessel to pour the contents. To enhance the stability of tall vessels, the shoulder is often placed closer to the base, creating an ellipsoid or ovaloid shape with a lower center of gravity, as in the Andean *aryballos*. Vessel supports may increase stability if they broaden the area where the vessel rests on a surface, but they may also raise the center of gravity.

The base of a vessel is important to stability during any use: storage, processing, or transfer. Stable vessels generally have broad, flat bases in addition to a low center of gravity; they are often described as squat (e.g., fig. 13.6*i*). Certain activities, such as cooking, may favor other base shapes. The contours of cook pots with rounded or pointed bases expose a greater surface area to the flames—the base as well as the sides of the vessel—for more efficient heating. However, for stability they must be positioned over the cooking fire by some sort of suspension or support, or set into the fire, which may cause excessive thermal stresses. Because a flat base joins the vessel wall at an angle, this shape may not be most efficient because of thermal differentials. For certain mixing actions an indented or annular base might offer less resistance and friction as the vessel is turned, and may be found on water jars that are carried on the head.

Transportability or ease of moving a vessel is a consequence of form, size, weight, and a quality that may be called “graspability,” “hold,” or “purchase,” related to moving the vessel in difficult circumstances. Such circumstances might include handling a vessel that is that is wet and slippery, or is hot or has hot contents, or is large, heavy, and difficult or awkward to support or carry. The features affecting hold are not so much the primary form characteristics as the secondary ones, such as handles or flanges that provide grip or leverage and protect against high temperatures. A large base or supports might provide the same advantage in handling a hot vessel. Handles are not necessarily intended only for lifting or carrying vessels; they also may be used for maneuvering and tilting vessels to pour out the contents, or to attach covers.

25.2.3 Functions and Forms

It is useful to summarize these complex data by returning to the major functions of pottery container facilities: storage, processing (or transformation), and transfer or

transport. Overall, however, the relations between vessel form and function are not at all simple and require several cautionary observations: some container functions can be performed with different shapes of pots; the same vessel shape can occur in several sizes, each with different functions; and some formal-functional distinctions are extremely subtle. An example of this last is found among the Kalinga, whose rice cooking pots and meat-vegetable cooking pots are nearly identical. Rice pots can be distinguished, however, by a relatively more restricted aperture, steeper rim angles, and a lower ratio of aperture to height (Longacre 1981: 54; Skibo 2013: 33–34, fig. 4.4).

25.2.3.1 Storage

Storage "is a fact of economic and social life in all cultures, at all times and in all places" but it has not been studied or theorized as an economic process to the same extent as production and distribution (Halperin 1994: 167–90). Pots for storage may vary in composition and in their primary and secondary formal characteristics depending on the nature of their contents (liquid or dry), on whether they are intended for long- or short-term storage, and on how frequently their contents are accessed. A survey of ethnographic data suggests that liquid storage vessels may be more variable in shape than dry storage vessels; liquid storage vessels are relatively taller as an aid to pouring, while long-term dry storage vessels may be relatively short and squat (Henrickson and McDonald 1983: 632–33; cf. Birmingham 1975: 371). Contrary to expectations, these vessels do not necessarily have restricted orifices and necks to prevent loss of contents or for easier covering and closing of the mouth (Henrickson and McDonald 1983: 633).

Vessels used for long-term storage or that are infrequently accessed are generally large and when full are too heavy for easy movement. They may be set into the ground or floor for stability. Closure or containment security (Braun 1980) is related to the storage function, indicating how tightly a vessel can be closed or covered to prevent spillage or other loss of the contents. Thick walls or a thick base may be desirable to increase stability, deter pests, and keep moisture in or out of the vessel.

25.2.3.2 Cooking

Vessels used in food processing activities that do not involve heat, such as grinding or mixing, also may have thick walls to be stronger and more resistant to sharp blows during pounding or stirring. Vessels used with heat, however, reflect complex design considerations. In principle, cooking vessels (fig. 25.2) should be engineered to make efficient use of the heat from the cooking fire.

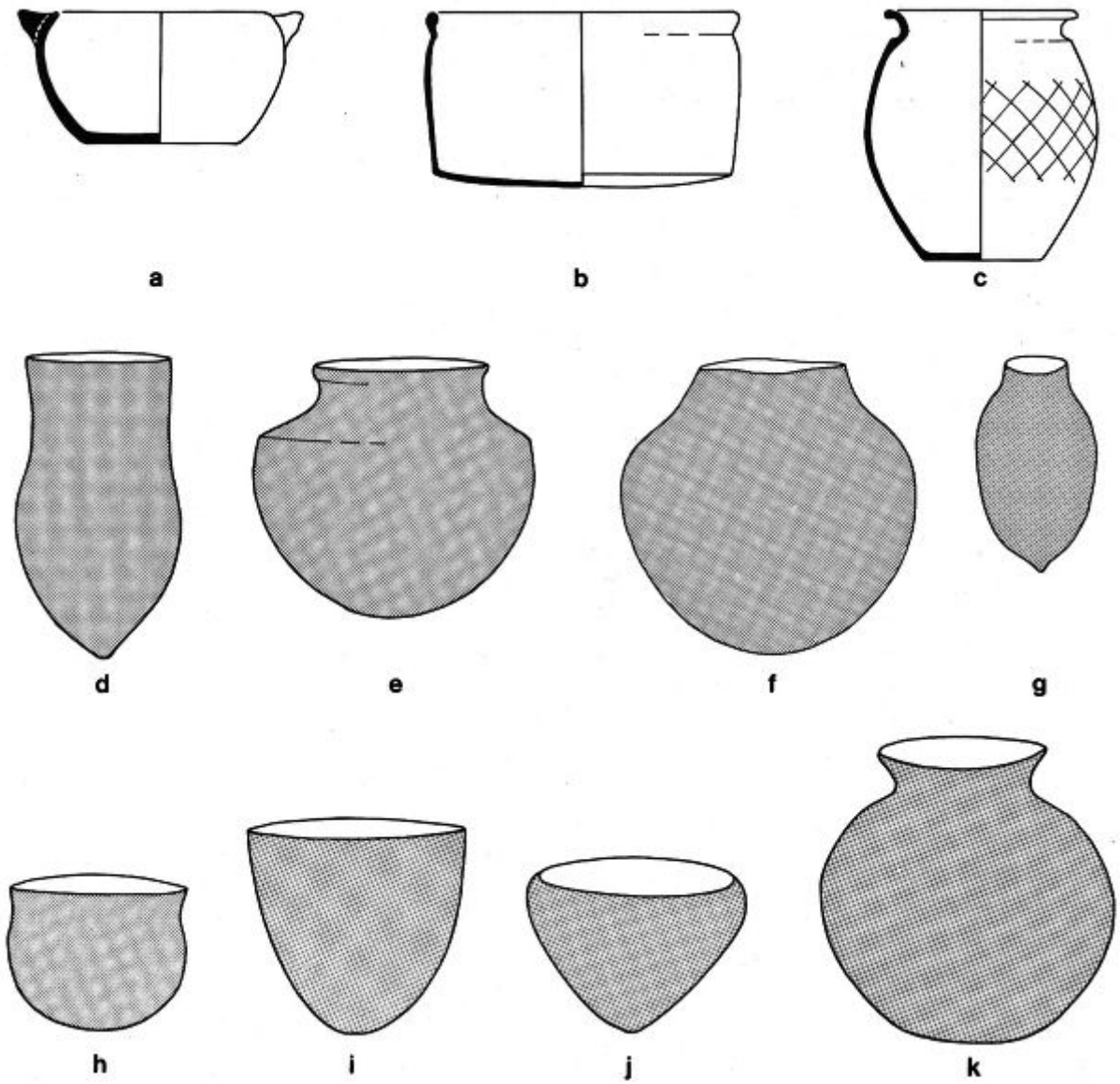

Figure 25.2 Variations in cooking pot shapes, ancient and contemporary: *a*, olla from modern Jocotán, Guatemala (height c. 16.5 cm); *b*, thirteenth-century cooking pot from Gloucester, England (diameter c. 40 cm); *c*, black-burnished ware from Roman Britain; *d–k*, modern cooking pots from three provinces in Papua New Guinea—*d*, Madang Province (height 37 cm); *e*, Madang Province (height 29 cm); *f*, Madang Province (height 19 cm); *g*, Madang Province; *h*, Mailu Island, Central Province (height 22 cm); *i*, Morobe Province; *j*, Morobe Province (height 27 cm); *k*, Morobe Province (height 34 cm). Sources: *a*, after Reina and Hill 1978: fig. 45*a*; *b*, after Vince 1977: fig. 2, no. 4; *c*, after Orton 1980: fig. 2.2; *d*, after May and Tuckson 1982: fig. 8.44; *e*, after May and Tuckson 1982: fig. 1.5; *f*, after May and Tuckson 1982: fig. 1.6; *g*, after May and Tuckson 1982: fig. 8.40; *h*, after May and Tuckson 1982: fig. 3.5; *i*, after May and Tuckson 1982: fig. 1.8; *j*, after May and Tuckson 1982: fig. 6.23; *k*, May and Tuckson 1982: fig. 1.7.

Boiling seems to be or to have been the most common aboriginal cooking technique in many culture areas (Hally 1983b; Lischka 1978: 229; Solheim 1965: 257; also Linton 1944), so many morphological characteristics of cooking vessels may be adaptations to this pattern of use. A survey of ethnographic data suggested an emphasis on short, squat shapes (Henrickson and McDonald 1983: 631). Pots are likely to have a relatively open orifice for adding and removing food, but a slight constriction or a low neck helps prevent boiling over and reduces evaporation. They generally have smooth, simple or

"inflected" contours, which permit greater exposure of the base, walls, and contents to the heat. They usually do not have sharp corners or angles, as in composite or complex forms, which would collect moisture and cause uneven heating and thermal stress over the fire (Rye 1981: 27). This point has been critiqued, however, on the basis of the occurrence of flat-bottomed cooking pots in many times and places (Woods 1986).

Vessels for simmering or frying may be more open and have flatter bases, intended to be raised slightly above the fire rather than set in it. Utensils for drying, toasting, or parching—such as griddles or *comales*—are usually but not invariably open and nearly flat, with little to no rim curvature.

Cooking pots might also be expected to be relatively thin-walled, to conduct heat better, cook food faster, and save fuel (cf. Henrickson and McDonald 1983: 631, who note thick walls in their ethnographic sample). Thin walls increase thermal shock resistance and reduce the thermal gradient by allowing liquids to convert to steam more rapidly and not build up in the walls. Further, cooking vessels are ideally coarse-textured, porous, and tempered with materials that have low coefficients of thermal expansion (e.g., calcined shell, crushed potsherd) to accommodate thermal stresses (see sec. 19.1).

The contradictions between expectations and ethnographic reality vis-à-vis the shape and thickness of cooking pots highlight the need to consider multiple factors in inferring vessel function. These factors include the properties of the resources available to the potters and the role of custom and habit underlying their decisions, which will be related in turn to the traditional items being cooked and the ways of preparing them.

25.2.3.3 Transfer

Transfer functions may pertain to short distances, as in presenting or serving food, or long distances, when the vessels may also have an implicit storage function. Vessels for serving and eating are likely to vary greatly in size depending on the number of people partaking (Henrickson and McDonald 1983: 632, 634). They are usually open for easy access to and perhaps visibility of the food; they may have a flat base or supports for stability. Secondary form variations are likely to be elaborate: flanges and handles can be for decorative display as well as for grasping a hot vessel as it is carried or passed; spouts aid in serving liquids and preventing spills. Another aid in handling a vessel filled with hot liquid may be thick walls, which conduct less heat from the contents to the outside. Because vessels for serving and eating may be used in relatively formal situations or with individuals outside the immediate family, they may display fine surface finishing and elaborate decoration.

An important consideration in the transfer function is the weight of the vessel, especially if the contents are liquid. This is especially pertinent for water jars, because water weighs approximately 8.3 pounds per gallon (1 kg per liter). The capacity of water transport jars may be relatively limited, between 2 and 4.5 gallons, weighing 18

to 35 pounds when full, before exceeding the maximum weight for convenient carrying in the customary manner (fig. 25.3).

Ceramic vessels may be used for long-distance movement of goods, perhaps in tribute or in trade: consider, for example, the millions of pottery amphorae that filled the holds of ships plying the seas in Mediterranean and Spanish colonial commerce. Such vessels serve in both transfer and temporary storage functions, and both tight closure and easy handling are likely to be important. Thick walls may be a disadvantage because of weight, but they likely contribute strength and stability in transport. Corinthian amphorae would have weighed from 60 to 190 pounds and very likely had to be rolled to the ships or wagons for overland movement (Vandiver and Koehler 1986: 202–3).

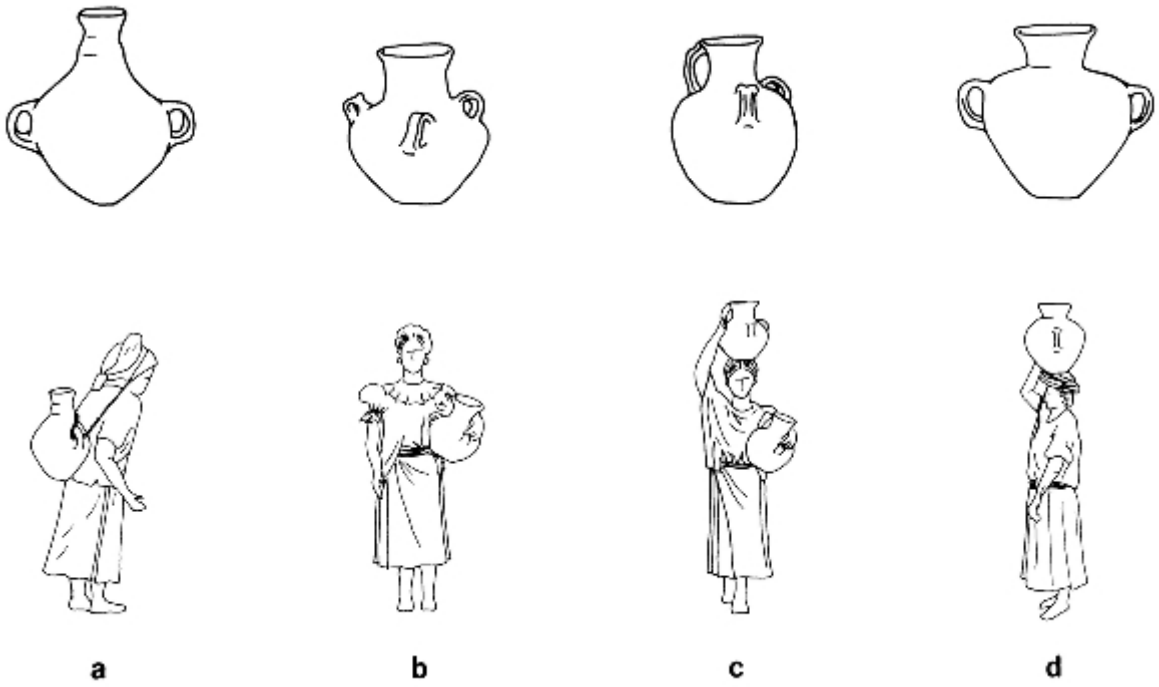

Figure 25.3 Different styles of *tinajas* (water carrying jars) in highland Guatemala and different ways of carrying them: *a*, northwest highlands; *b*, eastern highlands; *c*, southeast coast; *d*, north-central highlands. After Reina and Hill 1978: map 10.

On the other hand, the empty vessels themselves may be moved or traded; a wide-ranging pottery trade is known ethnographically. In some Spanish transatlantic wine shipments, the wine was carried to the New World ports in barrels, along with empty *botijas*, then off-loaded into the *botijas* for overland transport by mule train. Shallow, unrestricted forms can often be easily stacked or nested when empty (Whittlesey 1974: 108) and thus conveniently moved over considerable distances, particularly if they are relatively lightweight. Stackability depends on form and may be improved by lateral flanges or ridges (fig. 22.1; see Rottländer 1968).

25.3 Direct Evidence of Use

The functions of ancient vessels can be studied through several lines of direct evidence, many developed through ethnoarchaeological research (see Skibo 2013). Most investigate the processing and storage activities in which pottery containers may have been used.

25.3.1 Residues: Identification of Contents

One type of evidence for the functions of ancient pottery comes from the contents they originally held. This evidence is useful not only for cooking pots, where charring sometimes preserves the contents, and processing utensils such as graters, but also for storage and transport vessels. Because low-fired, unglazed vessels are usually permeable and porous, they are likely to retain residues in their walls as well as on the surfaces.

Residue analyses of pottery were pioneered in the 1960s, often by way of simple visual inspection (Clancy 1961; McPherron 1967: 47). Early residue analyses prompted many questions about methodology and the validity of results, and they were slow to be developed further. One major concern was the burial environment: because ceramic vessels are usually recovered from some sort of soil matrix, there was concern that the substances of interest would be degraded during burial (see Bowyer 1972: 331) or that concentrations might have been deposited from the burial environment. In addition, organic (especially resinous) substances detected on archaeological pottery might represent postfire additions to reduce the permeability of the vessels, rather than constituting stored or processed contents.

Residue analyses seek a variety of organic and inorganic substances, including phosphate, pollen, phytoliths, salts, resins, gums, carbohydrates (sugars and starches), fats, and oils. Beyond microscopy, typical analytical methods are those of organic chemistry, including gas chromatography/mass spectrometry (GC/MS) and infrared absorption spectroscopy, along with stable isotope analysis (see, e.g., Barnard and Eerkens 2007; Evershed 2008; Orton et al. 1993: 39–109; Malainey 2013). The spectrometric methods identify lipids such as fatty acids (plants and animals) in fats (e.g., triglycerides; from animal sources) and oils (mostly plants); also waxes, sterols (e.g., cholesterol), and other components of organic materials. At least one study of animal fat residues has distinguished dairy from carcass fats, and found that they occur in different-sized vessels (Copley et al. 2005). One analysis has showed that lipids may be differentially adsorbed onto different minerals, particularly binding to calcareous minerals (Goldenberg et al. 2014).

The phosphate (P_2O_5) content of a pot can be analyzed to determine whether the vessel held organic material. Phosphorus is an essential element for metabolism of all living things; it occurs naturally in all soils (including clays) and is concentrated in

areas of dense or prolonged human or animal occupation (e.g., houses or animal pens). In one study, experiments revealed that even when fired in the temperature range of 600–800°C, kaolin clays still had phosphate permanently bound to them; binding diminished above 800°C (Duma 1972). Phosphate was analyzed in unglazed pots from burials dating from the Neolithic period through the sixteenth century, using measurements taken in the earthen contents of the vessels, in the vessel walls, and in the surrounding earth. Enrichment of the phosphate content in all these areas, particularly on a gradient of increase from the mouth to the base of the vessels (though not through the vessel walls), was taken as evidence that the pots had originally contained organic material (Duma 1972). The possibility that they may have absorbed additional phosphate from an enriched surface (e.g., a house floor) was not addressed, however.

Other organic contents of vessels have been identified through a variety of techniques. GC/MS is particularly well suited to identifying organic materials such as oils and resins that volatilize; it is fast and requires only a small sample of material for quantitative analysis. The widely used amphorae of the ancient Mediterranean trade have been analyzed by FTIR and gas chromatography to detect traces of wine (tartaric acid, tannins, xanthocyanins) and oil in their pores (e.g., Arobba et al. 2014; Condamin et al. 1976; Formenti and Duthel 1995; McGovern and Michel 1995). GC/MS identified tartaric and other indicators of wine in traditional, archaeological, and experimental ceramics and plasters (Pecci et al. 2013). Similar analyses have detected residues of chocolate (cacao; *Theobroma*) in beaker-like vessels from the Southwestern and Midwestern United States after AD 1000, revealing trade with Mesoamerica (Crown and Hurst 2009; Washburn et al. 2011, 2013, 2014). Chromatographic analysis used on the contents of various jars and pots from early Bronze Age Crete suggested that one tub had been used in processing animal material, perhaps wool (Bowyer 1972). The contents of Neolithic and Roman period vessels were analyzed and showed evidence of milk, butter, olive oil, fish, pig, and mustard seed (Rottländer and Schlichtherle 1983: 37). A highly oxidized pine resin was identified in a Byzantine storage jar from Israel, possibly intended for use in caulking, waterproofing, or preparing an unguent (Shackley 1982). Analysis of lipids from a large number of early ceramic containers in northern Europe revealed the use of freshwater and marine fish and broadens interpretations of dietary changes that accompanied domestication (Craig et al. 2011). A liquid chromatographic analytical protocol has been found to increase recovery of fatty acids in Neolithic pottery from the Jordan valley (Gregg and Slater 2010).

With improvements in instrumentation and increased interest in pottery function in general, analyses have proliferated (see, e.g., Barker et al. 2012). One study of a common mass-produced beveled-rim bowl form in fourth-millennium BC Mesopotamia found, through experimentation and replication, that these vessels were likely used for baking loaves of leavened bread provided to the emerging cadre of bureacrats and administrators, rather than for unskilled laborers (Goulder 2010). Other recent studies have adopted experimental comparative approaches by pretreating modern ceramics in

various ways and then submitting them to various conditions for comparison with archaeological specimens. For example, some experiments have involved coating modern pieces of pottery with organics and then burying them in varied soils before analysis, to test for the possibility of degradation in the burial environment (e.g., Reber and Kerr 2012; Reber and Evershed 2004b).

Stable isotope analysis has been particularly useful in studies of the role of maize in ancient diets through the $\delta^{13}C$ signature of this C4 plant. Two kinds of stable isotope analysis have been used: compound-specific (Reber et al. 2004; Reber and Evershed 2004a; see also Hart et al. 2007) and bulk (Seinfeld et al. 2009). In an analysis of maize use in Olmec pottery, modern ceramics were soaked in maize beer and fermented beverages of made with C3-signature plants (manioc beer and a *balche'*-like honey wine) (Seinfeld et al. 2009). Similarly, a study of caffeine in the "Black Drink," a tea made from the holly bush (*Ilex vomitoria*) and used in indigenous rituals in the Southeastern United States, was carried out on modern pottery in which the beverage was brewed, and then the pottery was buried in varied soil conditions. GC/MS results showed good preservation of the caffeine (Reber and Kerr 2012). Additional *Ilex* biomarkers besides caffeine, including theobromine and ursolic acid, were identified in archaeological pottery beakers from the Cahokia site (Crown et al. 2012).

Carbonized residues from the charring of food during cooking may occur on the interior and rims of pots (Skibo 2013: 85–87, 96–99), as may residues from burning of resins or gums as incense. These encrustations may be AMS radiocarbon dated or analyzed to determine the contents if they have not been completely pyrolized (e.g., Berstan et al. 2008; Lampert et al. 2003). For example, starch grains from charred residues on cooking pots from southwestern Ecuador provided evidence of early maize cultivation 5000 years ago (Zarrillo et al. 2008). Similar carbonized residues provided evidence of early millet use 10,000–11,000 years ago in northern China (Yang et al. 2012) but revealed an absence of domesticated cereals in northern Germany (Saul et al. 2012). Deposition of residues depends on the temperature of the surface of the vessel, generally between 300°C and 400°C. Because the liquid of cooking keeps the interior surface at a significantly lower temperature, about 100°C, an interior "ring of carbonization at the water line is the use-alteration signature trace for cooking in the wet mode" (Skibo 2013: 97). This carbon deposit may penetrate into the interior of the wall.

Organic residues on pottery may include pollen, phytoliths, and starch grains, and recovery of these remains has provided data on use of plants in varied contexts. In the Maya area, cacao (chocolate) residues have been found in various Classic-period drinking vases and mixing jars (e.g., Hurst 2006), and Postclassic grater vessels from ritual contexts yielded evidence of *Datura* (a hallucinogen) and mammal blood in addition to maize and cucurbits (Cecil et al. 2010).

25.3.2 Sooting

The presence and location of soot deposits on the exterior sides and base of a vessel are clear indications of use in cooking or other activities involving fire. Soot is a black, powdery by-product of fuel combustion and, in the case of wood, is composed of carbon and organic tars and resins, including coke, char, and ash (Skibo 2013: 89). Soot adheres temporarily to the external walls of vessels and can be removed by washing, either by the users of the pot in antiquity or by the archaeologist. These deposits should not be confused with black or gray fireclouds, which may be a consequence of the original firing rather than use.

Figure 25.4 Examples of sooting on vessel exteriors: *a*, soot and fire blackening occur around the sides of the vessel while the base is lighter and more oxidized, indicating it was placed in a fire; *b*, soot deposits on both the base and sides of a pot, indicating it was placed above the fire (these "shoe form" or "boot shaped" pots from southern Peru may have been suspended by the handles over a cooking fire and are typically found in burials).

The most intensive study of vessel sooting patterns has come from ethnoarchaeological work with the Kalinga. Soot deposits on the exterior of a pot not only give evidence of the vessel's use with fire, but the location of the soot also tells how it was used with the fire (Hally 1983b: 7–10; Skibo 2013: 90–93). The major variables behind soot patterning are temperature of the fire and the pottery surfaces (soot is not deposited over 400°C), type of fuel, distance from the fire, and mode of cooking (wet or dry). If the soot occurs primarily on the sides of a vessel, from the base up to or near the maximum diameter, the vessel was probably set in the fire. Soot is deposited as a combustion product at the edges of the flames, and vessels used this way usually also have an oxidized or unsooted area in the center of the base (fig. 25.4*a*). Vessels that lack such an oxidized zone and instead have soot deposits on the base (and also the sides) were probably supported (typically by some kind of tripod) or suspended over the fire rather than set into it (fig. 25.4*b*). These vessels may have been used for simmering or frying; vessels placed in the fire were probably used for boiling.

The blackening of the pots by smoke and soot also would have increased their heat retention somewhat.

To take advantage of observations of sooting patterns in inferring vessel uses, care must be taken not to remove these residues when the sherds or whole vessels are cleaned in the field or laboratory (see Beck et al. 2002). It is also important to distinguish between in-use signs of burning and possible postdepositional alteration by fire, such as swidden burning. Systematic study of soot deposits is a recent endeavor, and it remains to be seen how the deposits may vary in regions where different kinds of cooking fuels are used that burn at different temperatures or have different compositions. Resins are more abundant in softwoods such as pine than in hardwoods, for example.

25.3.3 Surface Attrition

Additional inferences about vessel use come from use-wear studies that focus on attrition of the surfaces as a result of repetitive contacts or motions (Skibo 2013: 119–42; see also Bray 1982; Chernela 1969; Griffiths 1978; Hally 1983b). The degree to which a vessel will show traces of surface abrasion is a function of many factors, particularly the technological features of the ceramic itself: its composition (especially kind, size, and quantity of inclusions), surface treatment (presence of a slip or coating), firing, physical properties (e.g., hardness), and so on. It also results from the force exerted in any contact between the vessel surface and a hard object and the characteristics of that object (weight, hardness, size, etc.).

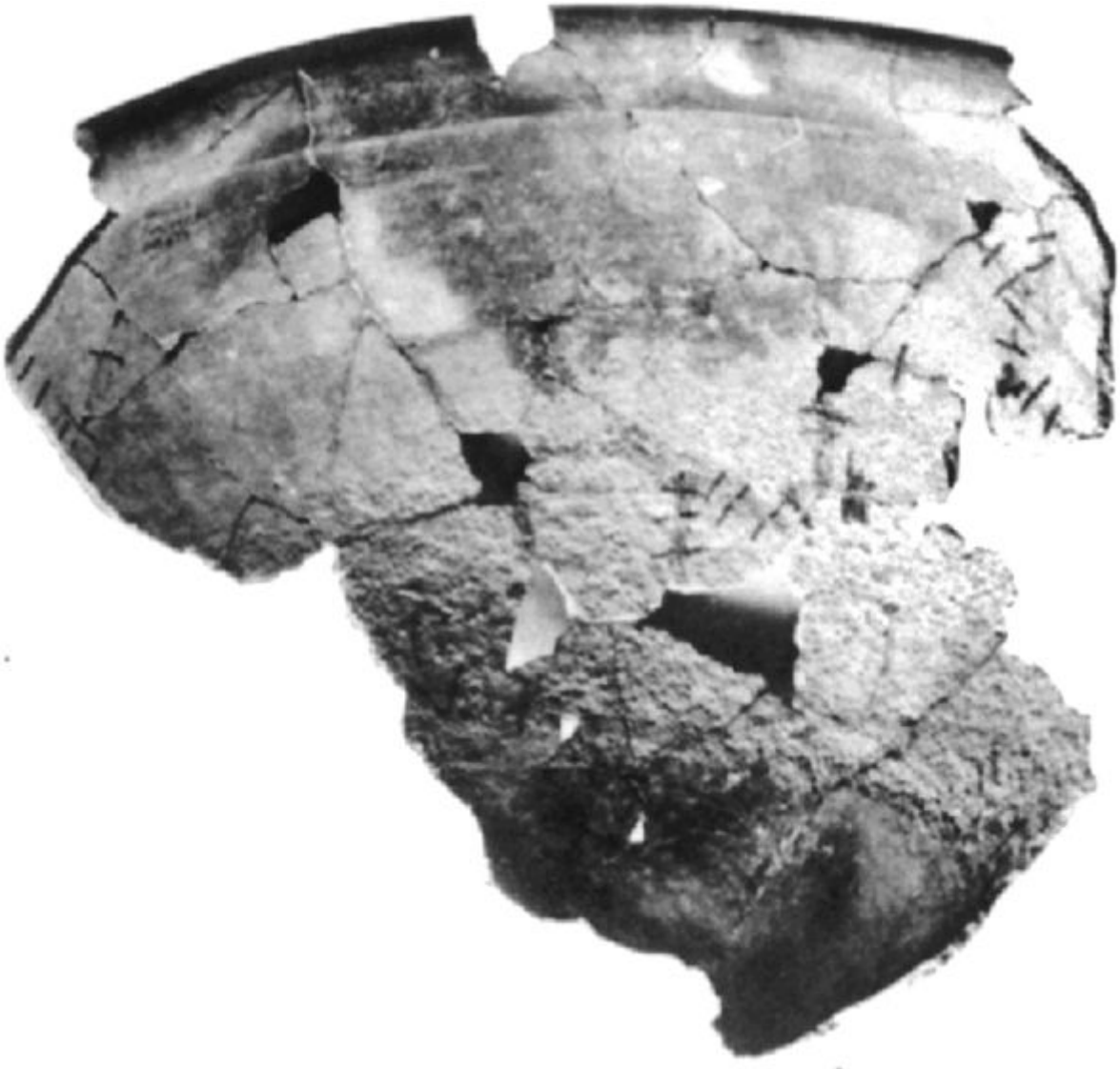

Figure 25.5 Interior of a fragment of a large jar from northern Georgia, showing a band of pitting thought to be caused by chemical action of solutions used in food preparation, perhaps fermentation. Photograph reproduced with permission from David J. Hally, "Use Alteration of Pottery Vessel Surfaces: An Important Source of Evidence for the Identification of Vessel Function," *North American Archaeologist* 4, No. 1 (1983): 3–26, fig. 6c; © Baywood Publishing Company.

Areas most likely to show abrasion, scarring, or chipping are the interior base, the interior sides (especially at and below the rim), and the exterior base. On interior surfaces, use wear is commonly seen as a result of processing, such as stirring, scraping, mixing, grinding, or pounding the contents, leaving striations, pitting, or patchy abraded areas (fig. 25.5). The lip or edge of a flange of a serving vessel or a wide-mouthed jar often displays chipping and erosion, especially of a slip, if present, through contact during access or careless positioning against hard surfaces. The exterior base similarly may be worn from repeatedly setting or scraping it on a hard and uneven resting surface, or from turning the vessel during mixing. Interior and exterior surfaces also may be abraded during cleaning by scouring with sandy materials.

Some usewear traces result not from contact with another object but rather through the action of the contents in the typical permeable and porous fabric of low-fired pottery. This may be seen as salt crystallization or thermal spalling under some circumstances (Skibo 2013: 122–23). Pitting or spalling around the upper interior of large vessels also may be caused by the physical and chemical action of fermentation, suggesting that a vessel had been used to make beer or wine (Skibo 2013: 152–55; see also Arthur 2002, 2003). This observation is useful with respect to interest in feasting as part of lavish political and economic displays. Unexpectedly, the 1000+ large earthenware wine jars in Moquegua, southern Peru, used in the valley's Spanish-introduced wine and brandy industry, lack these signs of fermentation. This might indicate that the jars were used for storing the wine rather than fermenting it, or it could be a consequence of careful compaction of the interior surfaces through a "reverse" paddle-and-anvil finishing technique involving forceful pounding of the interior rather than the exterior (Rice 1998: 345).

Use-wear traces may be very faint or distinct and substantial, removing the surface finishing and exposing the underlying paste. They may be difficult to see on excavated ceramics if the surfaces are badly eroded by the depositional environment. Further, because the patterns may be extremely localized, it is difficult to carry out use-wear analysis on sherds; sizable collections of complete pots yield much more reliable inferences.

25.4 The Hegemony of the Cookpot

It has been suggested that because of the importance of cooking pots in household assemblages, adaptation to thermal stress is the most important determinant of vessel composition. That is, in preparing clay for pottery making the primary consideration is "to give suitable physical properties for cooking pots; for other purposes vessels are either also suitable or are modified subsequent to firing" (Rye 1976: 119). This proposition makes intuitive sense, given the role of thermal stresses in causing failure of a ceramic. In addition, many vessels are described as being "cooking/storage" vessels, a dual usage that is probably common and important for archaeologists seeking to ascribe functions to archaeological pots.

The problem with this position, however, is that many of the predicted relations between cooking functions and composition do not hold true in "real life" among past and present makers and users of traditional pottery, nor do relations of form. Pots exhibit characteristics reflecting particular modes of cooking or particular kinds of foods, which doubtless account for the wide range of shapes in cooking pots, past and present. These points raise questions—probably unanswerable—of causality: Did potters choose their resources to optimize function, or did the users adjust their cooking techniques for preparing local foods to accommodate the properties of local pots made with locally available resources? Or some combination of both?

Similar cautions need to be considered in drawing inferences between modern industrial characterization and archaeological pottery. This point may be illustrated by considering, for example, the validity of comparative tests between a vessel of a "natural" clay containing a kaolinite component, hand-formed into a jar and fired in an open bonfire, and a test bar of a standard kaolinite clay mineral mixed with a measured amount of quartz of known purity and particle size and fired under regulated rates of heating and a soak of 100 hours in the controlled atmosphere of an electric-fired kiln. Most pottery recovered archaeologically is manifestly incomparable with commercial testing conditions or with commercial or art ceramics. How does archaeology illuminate the challenging trade-offs of engineering, where optimizing one process normally decreases performance of another?

A major objective in studying ancient pottery from a technological viewpoint is to understand firing technology and its implications for the final ware. Many times these studies take the perspective of modern commercial ceramic standards and conditions as a basis for comprehending and evaluating the variables involved. Yet the conditions of much non–kiln-fired pottery manufacture are not directly parallel to those of modern industry. This is particularly evident in discrepancies in the relations of time and temperature. Throughout much of prehistory and even in modern times, potters firing their wares in bonfires or with other mixed firing strategies have heated them only a fraction as long, and at lower temperatures, compared with commercial firings. Thus, it

is debatable whether many of the changes, both desirable and undesirable, known to occur in laboratory ceramic bodies at equilibrium also take place in open-fired terracottas.

Ceramic engineering tests can be used only with great care to retrodict the specifics of ancient production, because for much of the past the parameters of resource selection, forming, firing, and distribution are largely unknown and may be approached only through cautious inference. These tests do, however, provide a framework for understanding the development of the distinctive characteristics that for millennia have made ceramic materials so useful as utensils. And they share a concern with the costs of the fuel for balancing time and temperature requirements—either raising the temperature (for a shorter time) or increasing the soaking time (at a lower temperature)—in creating a functional object. If due caution is employed in their interpretation, the investigations carried out as part of commercial operations let us appreciate the sophistication of ancient potters in successfully manipulating raw materials—clay and heat—to achieve their desired ends.

Part 6

Then and Now; Now and Then

The hallmark of a successful potter is to have stopped potting.

David and Hennig 1972: 25

26 The Humility of Things

> . . . what I called the *humility of things* . . . . objects are important, not because they are evident and physically constrain or enable, but quite the opposite. It is often precisely because we do not *see* them. The less we are aware of them, the more powerfully they can determine our expectations, by setting the scene and ensuring appropriate behaviour, without being open to challenge. They determine what takes place to the extent that we are unconscious of their capacity to do so.
>
> Miller 2010: 50

Low-fired clay pots are humble things. It is, after all, hard to "make mud glamorous" (Deevey 1970: 5). With some notable exceptions, pottery generally is not viewed as a highly valued prestige good, like gold or jade, bedecking the residences and tombs of the upper stratum of society. Although certain kinds of ceramics may have been confined to elite, ceremonial, or mortuary usage—porcelain headrests, tea jars, life-size statues—pottery as an artifact class is not so restricted. Pottery served prosaic, day-to-day functions in cooking, storage, and hygiene for all ranks of society. Thus archaeologists and anthropologists encounter varied goods made of fired clay, from ordinary bowls and jars to baby bottles in Greece (Noble 1972), footscrapers in Pakistan (Rye and Evans 1976: plate 49b-3), and female pubic coverings in Brazil (Palmatary 1950: 327–28; Prous 2013).

Worldwide, the numbers of potters producing traditional forms, using traditional materials and traditional techniques, are fast dwindling. In particular, cooking pots are ceasing to be made. Few if any potting communities or their products have been untouched by the past six centuries of colonial conquest, missionization, capitalist expansion, and globalization. Incorporation into twentieth- and twenty-first-century international economic and political structures has, minimally, transformed the potter's work and in some cases brought its demise. This chapter examines some of these changes and their implications for analogies to, and studies of, pottery in antiquity.

26.1 The Humility of Pottery

Although expansionist states have impinged on production systems and distribution networks for at least four millennia, the effects of these interactions were not of the same magnitude as the events of more recent history. Since the late fifteenth century and the Age of Exploration, the world has seen exploitative commercial colonization of the entire globe, appropriation of resources and transfers of production technology on an unprecedented scale, and establishment of a worldwide monetary economy.

Traditional pottery production is an infinitesimal cog in the modern international economic wheel, but even in this humble arena—or perhaps precisely because of that humility—the repercussions of broader changes can be felt. Four transformations wrought by recent international economic integration have influenced pottery making: imposition of a cash economy, rapid communication and travel, convenient substitutes for traditional utilitarian goods, and increased national and international tourism. New methods of industrial manufacture and more efficient transportation have made cheap, mass-produced articles of plastic, metal, or china widely available even in remote areas. These materials of modernity cannot be easily acquired by traditional exchange or barter, because they are part of the money economy imposed through other means, but handmade goods such as traditional pottery provide economically marginal peoples with sources of needed cash. Furthermore, the growing influx of tourists desiring souvenirs of their travels in exotic locales has created a new market of consumers.

Although these entangled processes have stimulated interest in pottery making in some places, other independent factors have often operated to its detriment. Fuel shortages, for example as a result of deforestation, have played a significant role in the decline or abandonment of pottery making or have required elaborate arrangements to obtain nontraditional fuels, often from appreciable distances. In addition, the lure of urban life—education, jobs, and social and financial advancement—has drawn many from the younger generations out of pottery making into alternative economic endeavors, especially in rural regions (Lackey 1981: 126; Nicholson and Patterson 1985b: 236–37). Because children often are an important source of labor as well as heirs to the family business, this means that the occupation is gradually disappearing. In Guinhilaran, Philippines, pottery making has declined in all generations in one family, a process that began decades ago:

> The women, when interviewed, gave the following reasons for quitting pottery making: (1) age, (2) illness, (3) need to do other things such as housework, and (4) the lack of a man to get clay for them. As for the working children it would seem that the availability of better economic opportunities was the deciding factor. This reason is frequently given to explain why male potters will leave off potting for almost any other job. Informants say that women have to be potters since they can't get away from the home. This is, of course, another way of stating that wage work, when available, is open mostly to men.
>
> *(Scheans 1977: 22–23)*

When potters strive for some degree of upward mobility, this often means becoming a merchant rather than a manufacturer of pottery. In Los Pueblos, Mexico, success is measured not through artistic recognition but by ownership of a truck. Trucks make potters far more independent, and they save labor in all stages of producing and marketing pots, from acquiring and processing the clay to obtaining fuel and transporting the products to market (Papousek 1981: 120). Here, as in Guinhilaran and among the Fulani, “the hallmark of a successful potter is to have stopped potting” (David and Hennig 1972: 25).

26.2 From Today to Yesterday

Contact between cultures has been a constant in human history, often with deadly consequences but sometimes more peaceably. Complex questions surround continuities and changes in the various materialities these cultures represent and how differences are accepted and assimilated, or rejected.

26.2.1 Change: The "Arts of Acculturation"

Many kinds of traditional goods, along with their modes of production, have been transformed to accommodate the modern global marketplace (e.g., Nash 1993). A large proportion of this hybrid corpus, which subsumes many media and includes painting, carved masks, woven textiles, jewelry, and other goods besides pottery, is regarded as art rather than as more prosaic utilitarian "craft" goods or commodities (see Gell 1996), and more specifically as "arts of acculturation" (Graburn 1976). They are also referred to as folk, popular, transitional, ethnic, provincial, commercial, or urban art, terms more or less neutral in their connotations; other terms, such as souvenir art, tourist art, and airport art, may be pejorative.

The arts of acculturation have been grouped into various classes (Graburn 1976: 5–8), depending on their sources of inspiration—which may be the minority versus the dominant society; or internally versus entrepreneurially motivated (Gilber 1996)—and their intended consumers (inside or outside the producing society). To some extent, the degree of financial profit versus aesthetic motivation for their creation is also integrated into these classifications. Although it is often difficult to demarcate them, three categories are perhaps most important with respect to pottery: functional, commercial, and souvenir art.

Functional art or ware is largely directed toward the producing society and consists of pieces that have remained generally faithful to traditional materials, shapes, decorations, and uses in that society. This ware may be found in areas where relative geographical or cultural isolation has precluded continual economic contacts with tourists or art buyers, or it may be produced along with items that are more clearly oriented to an exterior market (fig. 26.1). In contrast, both commercial and souvenir art are directed toward external purchasers. The products represent varying balances of traditional standards against accommodation to varied consumers' needs (or artisans' perceptions of them). Of the two, souvenir or tourist ware (pottery or other) is less valued, because standards of production are often lowered so the output will sell profitably (inexpensively and in quantity).

Figure 26.1 A pottery stall in the main market in Guatemala City in 1974, the middle two shelves displaying "urban ware," such as vases, candle holders (including *angelitos*), flowerpots, and a variety of dishes (see also fig. 11.3). Note the white slip and appliquéd flower decoration. These hand-built and open-fired whiteware forms are no longer produced in Chinautla, north of the city, and *angelitos* are now moldmade. The lower shelf holds utilitarian glazed wares made in the western Guatemala highlands.

As recognized implicitly, if not always explicitly, to be successful souvenirs should be cheap and portable as well as understandable, dustable, and sometimes useful (Graburn 1976: 15); authenticity is rarely an imperative (see Phillips 2006). In accordance with these guidelines, objects in the arts of acculturation frequently are markedly different from traditional items, reflecting trends toward miniaturization (fig. 26.2), elaboration, simplification, secularization, and archaism (e.g., see Brody 1976: 74; Graburn 1976: 15–23). Innovations in ceramic tourist art often occur in forms that replicate Western objects such as ashtrays, candle holders, or planters; they may also include figurines of animals or people.

Figure 26.2 A young potter in Margaurites, Crete, throwing miniature jars "off the hump" on a kick wheel. Photograph by Lynnette Hesser.

In ancient times, culture contacts or conquests also had a role in transforming material culture (although not in creating airport art), and it would seem that there might be analogies between some of the changes occurring in the modern world and those of the past (Card 2013). That is, a better understanding of changes in modern pottery making and use should lead to a better understanding of those processes in the past. And the opposite should be true as well, with the changes identified in antiquity informing on those of the present.

26.2.2 Decoration and Style

A trend toward simplified finishing and decoration of pottery has been widely noted as accompanying social upheavals and dislocations, such as European contact and

conquest in central Mexico (Charlton 1968: 98, 1976: 521), Venezuela (Cruxent and Rouse 1959: 58–59), and North Dakota (Deetz 1965). A critical factor underlying the relative amounts of change is the symbolic content of the expression, especially in conditions of conquest and colonialism:

> The triumph of one culture over another is usually marked by the virtual cessation of the art of the vanquished, and its replacement by the art of the conqueror. When the offending objects and monuments finally cease to correspond to any living behavior, they become symbolically inert. They then are "safe" to play with in recombinations emptied of previous vital meanings, as in tourist souvenirs, antiquarian reconstructions, or archaizing revivals.
>
> . . . The linguistic separation of the populace into Spanish- and Indian-speaking groups [in the New World] strengthened the emerging division of colonial society as exploiting and exploited groups. Under these conditions, all symbolic expressions, including those of native origin, eventually became reinforcements of the power of the colonial state. As such, they are extensions of European art rather than native survivals.
>
> *(Kubler 1961: 15)*

Such changes are particularly important in a medium such as pottery, which has varying —but often high—degrees of integration between symbolic and utilitarian forms.

Sometimes the changes involve subtle combinations of characteristics. For example, "Colono-Indian" or "colonoware" pottery (Ferguson 1980; Wheaton 2002), produced in the Southeastern United States during the seventeenth and eighteenth centuries, shows a mixing of European shapes with traditional indigenous traits as well as African characteristics (especially decoration), perhaps associated with intermarriage. In the Dominican Republic, indigenous potters (likely under Spanish direction) produced wheel-thrown and hand-modeled wares exhibiting Arawak designs on European forms (Ortega and Fondeur 1978). Similar syncretism between European and native ceramics has been noted in contact-period wares in the Andes (Tschopik 1950: 205), where glazes and European motifs sometimes appear on traditional Inca aryballoid jars, and in sixteenth-century Mexico City (Lister and Lister 1982: 34–40).

The trend toward simplification in modern versions of traditional products is not necessarily characteristic of goods directed toward an art market, because art patrons may pay top prices for well-executed objects for their aesthetic value. Simplification does, however, tend to characterize tourist art by speeding up production for an undiscerning market. For their own functional goods, artisans may maintain higher standards (e.g., Lathrap 1976: 207). The transformations are particularly evident in finishing and decoration, with reduced attention devoted to particularly time-consuming steps such as burnishing, polishing, slipping, or decorating. Shipibo potters in eastern Peru, for example, known for the very intricate fine-line painted decoration on their wares (fig. 26.3), have increasingly simplified the decoration on tourist pottery, reducing the number of brushstrokes, sometimes omitting the fine-line work entirely and at other times emphasizing broad areas of color to heighten the visual impact of a piece at a distance (Lathrap 1976: 203–4).

Another trend in the arts of acculturation is secularization: the tendency to remove or diminish the symbolic content of objects or their decoration, often as part of a rationale for allowing them to enter a broader exterior market. As a traditional society is transformed and norms and beliefs break down during acculturation, many sacred objects used in rituals lose their special significance and may be shown or sold to outsiders. Proscriptions still linger on many objects, however, such as Laguna and Acoma Pueblo ceremonial bowls with their distinctive stepped rim, which are inalienable and cannot be sold outside the community (see Gill 1976: 107).

Figure 26.3 Exterior design of a contemporary Conibo (Peru) *kënpo ani* (a large communal drinking bowl), painted in black and red on white. Diameter 29 cm. After Lathrap 1976: fig. 62.

Secularization can be linked to formal and decorative simplification or its opposite, elaboration, of traditional shapes and decoration by the symbolic content or messages contained in the elements. Decorative structures or layouts may exhibit more continuity

than motifs with a high symbolic content, and thus may be likely to be actively suppressed by a dominant society or colonial power. Simplification typically accompanies the loss of symbolic meaning. The survival of these expressions in the resultant art products depends on the extent to which the symbolic content conflicts directly with the values of the dominant society (e.g., indigenous "heathenism" versus introduced Christianity in the early Spanish colonial Americas). They may be suppressed and disappear if they are in sharp conflict (e.g., veneration of "idols" of wood or pottery), or they may undergo a transformation to a more neutral form or be a focal point of regional or ethnic expression. Thus the information content of pottery style and decoration may both vary and function differently under situations of conquest and colonialism.

26.2.3 Form and Function

Utilitarian pottery tends to resist dramatic changes because the vessels' traditional uses and contents resist change. Dietary patterns, like motor habits, are extremely stable and resistant to change. Utilitarian culinary vessels are also conservative because they are typically almost entirely devoid of overt symbolic loading that a dominant group in colonial or acculturation situations might view as threatening. Smaller utilitarian forms may correlate with acculturation situations, in which social stress is compounded by population dislocations and reductions through war or disease. Alternatively, if nuclear households join into extended family units, vessels may increase in size, as happened in the American Southwest, where the capacity of historical period Hopi bowls was as much as 100% larger than that of prehistoric counterparts (Turner and Lofgren 1966: 125).

Modes of using and carrying traditional pots such as water jars are particularly resistant to change. For example, communities in the Guatemalan highlands carry *tinajas,* or water jars, in distinct ways (see fig. 25.3): balanced on the head, resting on the hip, or supported on the back by a tumpline (Reina and Hill 1978: 242; see also MacEachern 1998: 119 for an African example). These motor patterns are paralleled by differences in size and shape of the jars, particularly in center of gravity, volume, and weight. They are reflected in consumer preferences, and communities identify with their own traditional jar shapes and reject those of other areas.

In the modern world, the peoples who continue to use pottery vessels for cooking and water storage are often poor and rural, and more likely to maintain traditional foodways and retain traditional shapes. In the nineteenth-century Southeastern United States, on the other hand, earthenwares were used for specialty cooking among the upper classes: "okra soup was always inferior if cooked in any but an old Indian pot" (Ferguson 1980: 21).

Many of these factors for and against change in pottery come together in its role in ritual and ceremonial life. Religion is a powerful force for conservatism, and this effect

will be felt where pottery vessels have important religious functions: traditional pottery ritual vessels are unlikely to be replaced by modern industrial products. In Bombay, for example, potters are a traditional occupational caste whose products are essential in various Hindu festivals and ceremonies (Lynch 1979: 7).

26.2.4 Production and Distribution

Potters tend to use customary clays and tempers, long-standing motor patterns, tools, and traditions in shaping, drying, and firing. The learned and practiced motor patterns of efficiently forming a pottery vessel, along with the associated risks during its drying and firing, are powerful forces underlying tradition and the seeming conservatism of potters. New techniques, commonly introduced in efforts at modernization, are frequently resisted because the unfamiliar new movements seem awkward and inefficient. For example, efforts to introduce the potter's wheel in various pottery-making locales, despite assurances of increased output, had little success (Foster 1962: 87–88, 1965b: 51). In Atolo, Philippines, the National Cottage Industry Board introduced a pivoted turntable to modernize the pottery industry there, and though potters initially bought the turntables they quickly discarded them. They said that "there was no time advantage to be gained and that they didn't want to pay seven pesos for such an item when *tagang* [a supporting and turning device], made from broken vessels, cost nothing" (Scheans 1977: 112). Dean Arnold (1979: 735) suggested that the integration of new motor habits into a potting industry takes place slowly, needing about two generations.

Many other reasons for continuity in traditional ceramics are technological. For example, the clay, temper, and pigment resources in an area are effectively fixed. Potters' practices of shaping, drying, and firing are accommodations to the mechanical and thermal properties of those resources, developed by long experience. Altering standard operations may be seen as unnecessary and potentially disastrous tinkering with safe and proven effective procedures, especially if they are considered to have connections to ancestors. Innovations such as wheels or kilns represent risk—short-term risk of failure with an individual vessel or batch of vessels, and long-term risk in using scarce cash for such a sizable capital investment. Where the risk is great, potters are less likely to innovate.

Fuel for firing pottery, particularly wood—the preferred fuel—is increasingly scarce. This is driving up its price and forcing changed firing strategies, a search for alternatives, relocation of manufacturing areas, or abandonment of potting as an economic pursuit. Potters in Chamula, Chiapas (Mexico), for example, bought tracts of woodland for a reliable fuel supply or abandoned their craft altogether (Howry 1976). In many areas of the world, especially on the fringes of large urban markets, potters effected a symbiosis with other industries, especially agriculture, to obtain nontraditional fuels. Thus not only does agriculture often produce the primary contents

of pottery vessels, but its by-products are major renewable sources of raw materials for manufacturing them.

The scarcity of firewood is especially a problem today in underdeveloped countries in the tropics, where wood may still be the primary fuel for cooking and heating, particularly in rural areas. These areas represent the last reserves of many of the world's hardwood forests, but unchecked development and population growth have rapidly decimated them through lumber exporting, ranching, and farming. In recognition of these pressures, there remains an urgent need for reforestation with fast-growing "firewood" crops, such as those that coppice naturally (National Academy of Sciences 1980).

The kinds and quantities of pottery manufactured by traditional potters may change in response to the transition to a cash economy. The need for, or availability of, cash may stimulate innovation. In Dangtalan, Philippines, the sudden cash influx brought by the opening of a nearby gold mine meant that villagers could buy prized plastic water containers instead of ceramic water jars, and the number of such jars in the village declined from eighty-eight in 1976 to fifty-two in 1980 (Longacre 1985: 345). Similar preference for new, nontraditional containers is characteristic of Bé, Cameroon (David and Hennig 1972: 25), where both potters and pottery are held in low esteem. In Yucatán, Mexico, the decline in demand for traditional pottery in general resulted in a breakdown of the customary pattern of product (possibly community) specialization, in which individual potters made only one or a small number of forms (Thompson 1958: 115).

The effects of acculturation are not confined to changes in production: traditional distribution patterns may be considerably altered as well. The most obvious changes in distribution coincide with the building of roads and access to trucks, as remarked in many ethnographic situations. However, other changes can occur: the traditional *kula* trade cycle by which pottery manufactured in the Amphlett Islands circulated to the Trobriand Islands was disrupted by European politico-economic meddling and by the replacement of seagoing canoes with motorized launches (Lauer 1971: 199).

26.3 From Today to Yesterday: Some Questions

Ethnoarchaeological and ethnographic observations have shed considerable light on the roles of potters and pottery in recent times. Given the political and economic circumstances of today's globalized world, however, the validity of analogies between present and past is open to question. There may be some topics and processes that are better illuminated by longer-term investigation or that simply cannot be examined in today's political and economic circumstances.

26.3.1 Status

In study after study of the economics of pottery making, the overwhelming conclusion is that traditional potters all over the world today are at or near the bottom of the socioeconomic scale (see Foster 1965; also Hodges 1974: 35; Nicholson and Patterson 1985a: 59). Only in a few areas are potters and their work held in any appreciable local esteem (see, e.g., Winslow 1996, 2000), and that is usually where skilled women potters contribute the major household income or earn significantly extra (see Crossland and Posnansky 1978: 82; Mijango 2001; Reina and Hill 1978: 21; Stone 1950: 278) or where individuals produce for a high-end tourist market and are considered artists (e.g., Lackey 1981: 38). In both situations, as pottery making becomes a significant source of household income, production tends to shift from women to male producers (see Longacre 2004). Most traditional potters seem to live in a precarious economic state, their expenditures equaling or exceeding income, with limited opportunity to amass extra cash and improve their lifestyle.

This situation is made even more tenuous by the overall declining market for traditional pottery. Where potters labor in workshops run by entrepreneurs, the economic situation is often worse: in the Liloan factories in the Philippines, the drop in prices and the reduced market resulted in a dramatic decline in the potters' income, but that of the entrepreneur stayed essentially the same (Scheans 1977: 65).

It is not unlikely that large cities in antiquity—Rome, Teotihuacan, Susa—attracted immigrants in much the same way that cities do today, for their employment and other opportunities. But were potters always of low status, even if they made or decorated high-status or prestige wares? Among the Classic Maya, the painters of some kinds of pictorial polychrome vessels were members of royal elites. In prehistoric times, before the advent of cheap metal or plastic containers, when utensils for rich and poor alike were ceramic—when pottery wasn't so humble—was a successful potter one who no longer made pottery?

As ceramic products move into a broader economic framework new statuses develop, attracting skilled, ambitious, and innovative individuals by the promise of a more prestigious role in society. Sometimes this may simply constitute an increase in the

esteem with which contemporaries regard a particular potter's work; other times a particular artisan or village may draw public acclaim for creating a particular style.

In areas of the world where a caste system dominates social and economic institutions, pottery making is a low-caste occupation. Is this because it is dirty, with the handling of earthy materials? One study has described as "profound" the effects of the caste system on "procurement, production, distribution, use, mending, reuse, and discard" (Arthur 2006: 6). To what extent might analogies be inappropriate between caste-like pottery making and use, as in much of Africa today, and that in communities subject to strong Christian proselytization, such as the Spanish colonial Americas?

Similarly, is the observed correlation between potting communities and poor agricultural land a consequence of the last five centuries of colonial domination, or can it be observed archaeologically as well? Can analogies to the modern "feminization of labor" be seen in premodern circumstances of major technological overhaul toward export economies, or is it specifically a consequence of industrialization, globalization, and wage work associated with capitalism? Pottery inventories were taken primarily in pottery-making communities in the late twentieth century: to what extent are these assemblage data valid for pre-industrial times before the advent of plastics and metal containers? Can perishable containers of basketry, wood, or animal skin be conceptually substituted?

26.3.2 Commodification and Specialization

A key element in reconstructions of past and present economies is exchange, whether it took place through barter, markets, or other mechanisms. At least three economic processes—commodification, specialization, and monetization—can be studied in ancient contexts but have relatively restricted opportunity for anthropological or ethnoarchaeological study today. How do processes of commodification relate to specialization? Specialized production of humble commodities such as pottery has been of little interest to ethnographers . . . perhaps because they did not *see* the pots, as Miller comments in the epigraph (see also Wells 2009). Consequently archaeologists lack convenient analogies to various productive structuring mechanisms in the past. A relevant question might be whether such specializations occurring under industrial capitalism would be similar to that of the past in any case (see Feinman and Nicholas 2007; Isbell 2007).

Box 26.1 Chinautla, Guatemala

One of the most powerful forces underlying ceramic change in situations of culture contact is the difference between the values of the traditional and the dominant societies, and the role of individuals. Chinautla, Guatemala, was a closed corporate community that placed great value on *costumbre*: traditional customs, practices, and conformity to community-wide standards of behavior (Reina 1966; Reina and Hill 1978: 231–51). Proximity to Guatemala City, the capital of the country, with its large open markets, Ladino consumers, and foreign tourists, inexorably drew the potters of Chinautla into the international economic web. With this opening of the closed community structure, potters gradually broke away from the restrictions imposed by *costumbre,* broadening their repertoire of shapes and techniques beyond the traditional *tinajas* that once identified a potter as a good *Chinautleca*.

Potters began producing twentieth-century "urban ware" (Reina and Hill 1978: 262): hand-modeled crèche sets, candle holders, doves, chickens, angels, madonnas, ashtrays, and a wide variety of nontraditional bowls, jars, and other containers (fig. 26.2). By the early twenty-first century, however, this repertoire of forms was reduced and the angels and madonnas were moldmade. Similar transitions to molding occurred in Ticul, Mexico (Arnold 1999).

The mid-twentieth-century changes in Chinautla were not easy because the necessary emphasis on innovation to meet the demands of an urban market constituted a rejection of *costumbre* and of corporate identity. The innovators themselves were often socially rejected (see, e.g., Reina 1963; also Díaz 1966: 213). A similar example comes from Sardinia, where a potter who changed the grate in his kiln to a nontraditional type that reduced wastage was ostracized by his colleagues (Annis 1985: 244).

In some areas production of new commodities and the economic success that results is seen as an individual matter rather than a manifestation of community solidarity. This trend may be shown in several ways: artisans more often sign their wares, and they may jealously guard their own formulas for forming, decorating, and firing pottery. In Chinautla, producing tourist wares for a wide market led to a competitive spirit that emphasized individual "ownership" of ideas and secrets for new products. Procedures for firing the new pottery styles particularly inspired possessiveness: in Chinautla these steps

> have been perfected by some of the best potters and are kept secret by the family. So, each potter involved in the production of urban ware finds out on her own how to succeed. "Intelligence is needed," remarked a potter, "before these innovations take place." In the solitude of each household and in the conservative ways of the community, each family guards their findings jealously. Producing urban ware is, after all, an individual pursuit, not yet a community tradition.
>
> (Reina and Hill 1978: 264–65; see also Foster 1965b: 57–58)

Ethnographic and ethnoarchaeological accounts of pottery making report the considerable influence, often community- or region-wide, of individuals in accepting the challenges of a new market with different standards and redirecting their artistic output toward that market. Potters such as Maria and Julian Martinez of San Ildefonso Pueblo (Marriott 1948) and Nampeyo of Hano in the Southwestern United States, Margarita of Chinautla, Guatemala (Reina and Hill 1978: 258), and Natividad Pena of Tzintzuntzan, Mexico (Foster 1948a: 95–99), for example, were significant in transforming their craft. These individuals—as well as such potters as Wasëmëa in Peru (Lathrap 1976: 203) and Àbátàn in Africa (Thompson 1969), who upheld more traditional standards, or the powerful monopolist don Asunción in Los Pueblos (Papousek 1981: 102–5), who influenced the production and marketing relationships of potters and middlemen—illuminate the role of strong personalities in economic development in ways that will never be achievable for the archaeological record of prehistoric ceramic change.

The monetization of ancient economies refers to the development of standard equivalents—money or currency, whether commodity money or coins, whether or not as "legal tender"—for use as an agreed-upon medium of exchange and determinant of "price." This process, referred to as equivalencies-formation, is identified as "*the* generic problem for understanding economies across cultures, because equivalencies play a part in all processes of material-means provisioning in cultural systems" including barter (Halperin 1994: 89–90, emphasis in original).

In its more specific form, referring to the development of money, monetization occurred at different times in different cultures (see Haselgrove and Krmnicek 2012) and is associated, minimally, with large, complex economies: large-scale production of various goods to satisfy a large body of consumers. The process developed unevenly, at least until the development of the Eurocentric world economy in the sixteenth century (see Davies 2002). Since then, monetization has been proceeding apace, particularly in the late twentieth century with the imposition of cash economies throughout the world. The question of interest with respect to pottery is, To what degree is pottery's role as a commodity in today's cash and plastic world comparable with that in nonmonetized antiquity? Perhaps pottery was not so humble in those days.

26.4 Change and Conservatism

Archaeologists use variations in styles and forms of pottery to develop site and regional chronologies, propose functions and uses of the wares, and reconstruct social, ritual, political, and economic behavior on both structural/institutional and individual/agentive levels. In doing so, analogies between past and present need to be treated with caution. The ubiquity, duration, and intensity of contacts between Western societies and indigenous peoples raise concerns about the legitimacy of certain aspects of both specific and general analogies between ancient and contemporary pottery producers and their products. No pottery-producing society has remained untouched by twentieth-century economics.

It frequently has been alleged that potters as a group are extremely conservative and resistant to change (see Rice 1984). This judgment has been made from two perspectives: study of contemporary potters and their attitudes toward introduced modernization schemes, and study of how changes in archaeological pottery correspond to changes in the broader social system. Concerning the first, attempts to modernize rural industries have introduced the wheel and kilns into communities where pottery is traditionally hand built and fired in open fires (Foster 1962: 143–44). Potters' refusal to adopt these modern capital-intensive technologies has sometimes been interpreted as reflecting a conservative basic personality structure or as backwardness. With respect to the second, investigations of the correlation between ceramic change in the archaeological record and known political, economic, or religious disjunctions in the historical record have concluded that ceramics are surprisingly unresponsive to changing circumstances (Adams 1979; Tschopik 1950: 217; van der Merwe and Scully 1971: 184).

It is also apparent that different kinds and degrees of change are associated with different ways of organizing production and probably also with the status of the producers (see Balfet 1965). The same responsiveness to change may be given different connotations depending on the gendering of production mode, however. Female household producers of utilitarian or domestic wares for intragroup use are often described as tradition-bound and conservative. In male workshop production units, on the other hand, similar adherence to a set of specific procedures and products, whether in mass manufacture of utilitarian vessels or tourist curios, is described with some approbation in terms of efficiency and standardizing.

Obviously pottery does change over time, qualitatively and quantitatively as well as through substitution and integration (see Loney 2000; Neff 2001; Schiffer et al. 2001). That is, formal, decorative, or technological attributes of pottery may be added, lost, substituted, or recombined. It is these changes that have allowed archaeologists to outline many of the cultural transitions in the history of occupation and in the development and spread of civilization throughout the world. But many forces for

conservatism underlie two major categories of traditional utilitarian pottery vessels: the water jar (Nicklin 1971: 20–21; Reina and Hill 1978: 238–43) and the cooking pot (Rye 1981: 27). The conservatism of these forms derives from several factors: (1) the familiar flavor imparted to water stored or food cooked in them (as a consequence of the clay composition and porosity); (2) the motor patterns involved in making and using them; (3) in water-carrying jars, the messages of group identification sent by their shape, mode of carrying, and any decoration; and (4) in cooking pots, the adaptation of the shape and other attributes to thermal stress resistance. Add to these specific factors the low socioeconomic status of people who continue to use clay household utensils today, their traditional dietary preferences, and their lack of exposure to variation or means of modifying their foodways (whether because of age, sex, or cost), and a powerful set of circumstances exists to maintain continuity and stability in utilitarian pottery manufacture.

For better or worse, modernization has opened heretofore "closed" traditional communities and integrated them into national and international economic networks. We do not know to what extent similar processes might have operated in ancient times—for example, accompanying urbanization or the development and spread of complex (state) societies. Although the processes might have been the same in the past, the transformation doubtless took longer than the one or two generations over which these events take place today. Thus while modern analogies can shed light on how acculturation affects pottery manufacture, it is questionable that any incidence of state expansion in earlier times is equivalent in scale to post–fifteenth-century European colonization.

All these considerations combine to make it frustratingly difficult to understand changes in pottery over the past millennia. One must have some awareness of historical and contextual differences between past and present to evaluate the extent to which modern potters are appropriate analogies for prehistoric artisans. Nonetheless, modern potters and their products provide a singularly valuable connection with an art, an occupation, and an industry whose roots go back ten thousand years or more in some regions. It is by incorporating ethnographic insights into technological and archaeological studies that this tradition can be most fruitfully illuminated.

Glossary

This glossary was prepared with reference to the following works:

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2004 *The potter's dictionary of materials and techniques.* 5th ed. A. C. Black, London.

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1984 *Ceramic glossary 1984.* American Ceramic Society, Columbus, OH.

Savage, G., and H. Newman

1976 *An illustrated dictionary of ceramics.* Van Nostrand Reinhold, New York.

absorption the process by which a liquid is drawn into and fills the pores of a permeable, porous body.

accuracy the correctness of a quantitative determination as a function of experimental procedures, standards, calibration, and possible systematic errors.

additive an organic or *mineral* material mixed with a clay by the potter to modify its properties in forming, drying, and firing; sometimes used interchangeably with *temper* or related terms; see also *aplastic, grog, inclusion, nonplastic, temper.*

adsorption the capacity of a material to accept and retain another substance (such as moisture) on its surface.

aggregate an inert component such as *grog* or potter's *flint* in ceramic bodies, especially *triaxial bodies,* analogous to the archaeological term *temper;* also called filler.

aging storing prepared ceramic material (usually a wet, plastic clay mass) to improve its working properties by thorough wetting of particles, slow compression, bacterial action (called souring), and other poorly understood processes.

alkaline glaze a relatively low-fired glaze with a high concentration of alkali metal elements (especially Na, K, or Li) in its composition, often having wood ash as a significant constituent.

anisotropic having physical properties that vary in different directions, particularly important in modifying the drying and firing behavior of ceramics and in optical crystallography of ceramic materials.

aplastic particulate matter in a clay body that does not contribute to plasticity or that reduces the plasticity of the clay; one of several terms used for *temper,* but lacking implications of either natural occurrence or deliberate addition by the potter; see also *additive, grog, inclusion, nonplastic, temper.*

apparent porosity the relation of the open pore space to the bulk volume of a clay body, expressed in percent.

archaeometry the segment of archaeological science that applies the methods of chemistry and physics to the analysis of archaeological artifacts, features, and sites.

archaeothermometry measurement of any of several properties of ancient pottery (including color, *porosity,* shrinkage, degree of *vitrification,* etc.) to determine the temperature range of its original firing.

assemblage an archaeologist's grouping of artifacts (such as pottery) from a site by form and function, assumed to represent the material culture of a single occupation or cultural episode.

atmosphere (firing) the gaseous composition of the air in the environment of heating and cooling clay articles, particularly with reference to the availability of oxygen; see also *oxidation, reduction.*

attapulgite one of several hydrous-magnesian clays with a lathlike or fibrous particle shape, characterized by a chainlike rather than a sheetlike atomic structure; related to *palygorskite.*

attribute a property or characteristic of style, form, or technology of an artifact that forms the basis for analysis; also called a variable, in which case "attribute" means the specific expression of the variable (see *attribute state*).

attribute state the value or score of a particular artifact with respect to a particular attribute or any of several alternative values; sometimes used interchangeably with *attribute.*

ball clay a fine-textured, highly plastic sedimentary clay, usually composed of the *mineral kaolinite,* typically containing considerable organic matter and firing white or cream.

band a design *element* or fundamental part that is continued or repeated along a straight line that, on pottery, most commonly encircles the vessel but may also be vertical or diagonal.

base (1) the underside of a vessel, or that part of a vessel in contact with the surface it rests on during normal use; sometimes called the *foot;* (2) chemistry: an alkali substance, a metal oxide with *pH* above 7.

base exchange capacity *ion* exchange or replacement; the capacity of *colloidal* inorganic materials, such as clays, to *adsorb* basic ions (e.g., calcium, magnesium, potassium) on their surfaces from the surrounding medium and to replace or exchange them with other ions in the medium.

bat (batt) a slab, disk, or board of plaster, fired clay, asbestos, or other slightly porous material used to dry a wet clay body by absorbing moisture from it, as a support in shaping an object from the clay, or as a detachable wheel head.

binder a substance, usually organic, added to a clay or glaze to increase its *green strength*.

birefringence the property of some crystals (*anisotropic* crystals) to split a beam of light into two beams that pass through the crystal at different speeds, producing characteristic optical effects seen under crossed nicols in a *polarizing microscope;* the difference between the largest and smallest *refractive indexes.*

biscuit (bisque) unglazed fired pottery, awaiting glazing: the first or preliminary firing of a ware that is subsequently glazed and refired in the *glost* firing.

body (1) clay or a mixture of clay and *inclusions* (*temper*) that is suitable for forming vessels or that has been fired into a vessel; often used interchangeably with *fabric, ware,* or *paste* and being closest to paste; (2) that portion of a vessel between the *orifice* and the *base,* also sometimes called the belly.

Bragg equation a statement specifying the angle at which X-rays are reflected from a crystal, as a function of the crystal-lattice spacing and the wavelength of the X-rays: $n\boldsymbol{\lambda} = 2d \sin \boldsymbol{\theta}$, where $\boldsymbol{\lambda}$ is wavelength, d is the lattice spacing, and $\boldsymbol{\theta}$ is the reflection angle.

burnish a method of producing a luster on an unfired clay surface by rubbing it while *leather-hard* with a hard, smooth object to compact and align the surface particles.

carbonate a compound that contains the CO_3^{2-} ion; a sedimentary *mineral* or rock made up of such compounds.

casting a process for forming a *ceramic* object by pouring a clay slip into a hollow, porous (usually plaster) mold and leaving it there long enough for a layer of clay to settle and thicken on the mold wall. The remaining slip is poured off, and the object is removed from the mold when it has dried. Also called slip casting or solid casting.

categorization an aspect of the classificatory process that consists of creating groupings within a previously unclassified set of objects (as opposed to assigning objects to existing classes); see *classification, typology*.

cation exchange capacity (CEC) the ability of a material, such as a clay particle, to adsorb cations (positively charged *ions*) from the surrounding solution. CEC relates to the negative surface charge of the silicate platelets, and increases with organic content and as particle size is reduced.

celadon a subtle, green, *reduction*-fired, iron-containing, feldspathic *glaze*; a *stoneware* ceramic having a glaze with a soft blue-green or gray-green color and satiny texture, similar to jade, produced by relatively low temperatures and reduction firing. High-quality celadons are particularly associated with the Song dynasty of China (AD 1127–79).

ceramics (or ceramic) (1) objects manufactured of *silicates* (primarily *clay*) and formed by application of heat; (2) in materials science, inorganic compounds produced by applying heat to metallic and nonmetallic materials; (3) in art and archaeology, high-fired, usually *vitrified* cooking and serving utensils and art objects (as distinct from *pottery*); (4) the research and applied fields developed around these products.

characteristic points points on the contours of a vessel silhouette or vertical section marking angles (corner points) or curvature (inflection points), used in one system of classifying vessel shapes.

characterization the qualitative and quantitative description of the composition and structure of a material so as to evaluate its properties and uses.

china clay another name for kaolin clay, usually specifically a white-firing *primary clay*.

chroma saturation, purity, or strength of color; in the *Munsell* system, chroma is the horizontal dimension, denoting the presence or absence of gray.

classification ordering objects into groups on the basis of their similarity with one another; classifications of pottery may be *folk classifications* (ethnotaxonomy) or *devised classifications,* the latter being more common in archaeology; compare *typology.*

clay (1) one of several hydrous alumina-silicate *minerals* formed by decomposition of rock and that have the property of *plasticity*; (2) an extremely fine particle size grade, less than 0.002 mm in diameter; (3) sedimentary materials composed of 35%–40% particles in the extremely fine particle size grade; (4) a fine-grained, naturally occurring material that becomes plastic and malleable when wet and hardens with the application of heat.

cleavage the tendency of some *minerals* to split along planes determined by their *crystalline structure.*

coefficient of thermal expansion the linear or volume expansion of a material occurring with a change in temperature, expressed per change in °C.

coil fracture a smooth-edged circumferential breakage characteristic of coiled vessels in which the coils were poorly bonded, resulting in planes of weakness.

coiling a method of hand building a clay pot by successive additions of ropes or coils of clay (variants include *ring building,* spiral coiling, and segmental coiling).

collar a raised and extended *orifice* that begins at or just above the point of maximum diameter of the vessel and does not significantly reduce the opening relative to the body diameter; see also *neck, throat*.

colloid a stable suspension of small particles, usually 1 μm (or 0.001 mm) or less in diameter, of some substance in another medium.

colorant a chemical element that contributes color to a mixture; see also *pigment*, *stain.*

complex shape a vessel shape that in silhouette is marked by two or more *characteristic points* of inflection, or changes in curvature, or by both corner and inflection points.

composite shape a vessel shape that in silhouette is marked by *characteristic points* of angles or corners, and lacks inflection points.

compound a substance comprising atoms of two or more elements, having relatively fixed composition and properties.

compression the *stress* of a crushing force applied to a material.

conductivity, thermal the ability of a material to conduct heat, symbolized by *k*; the rate of heat flow through a material, expressed as BTU per square foot per °F, or as watts per meter per °K.

cones (pyrometric cones) small, elongated pyramids made of controlled mixtures of ceramic materials in a numbered sequence that soften and bend when heated under specific conditions. When cones are placed in a kiln during firing, their bending provides an index of heat treatment and proper firing.

configuration the arrangement of decorative *motifs* on a vessel to fill a spatial division and form the design.

core (coring) a black or gray zone in the interior cross section of a vessel wall, usually associated with incomplete removal of carbonaceous matter from the clay during relatively low-temperature firing; not to be confused with black coring at high temperatures, which results from trapped gases and may lead to bloating.

countercharge color reversal; a term used in *symmetry* analysis of painted designs, in which colors alternate through repetition of fundamental parts.

crawling a defect in which the *glaze* separates from the body during drying or firing (e.g., around a prefiring crack), leaving unglazed areas.

crazing a defect characterized by a fine network of cracks in the *glaze,* occurring when the glaze is in tension because it shrinks more than the body.

critical point the point in the drying of a clay article at which *shrinkage water* has been removed, shrinkage has largely ceased, and the piece is rigid and *leather-hard;* also referred to as the critical moisture content.

crystal a material with atoms distributed in an orderly array (a lattice structure), having characteristic optical and physical properties.

crystal lattice water chemically combined water (as hydroxyls) held as an integral part of the layered *crystalline structure* of clay minerals, normally lost only with heating the clay to temperatures between 450°C and 600°C; distinct from *interlayer water.*

crystalline structure the regular arrangement of the atoms of a *mineral*; also lattice structure.

decay model (fall-off model) a graphic representation of economic exchange in which the frequency of occurrence of a commodity at a number of sites is plotted against the distance of those sites from the source of the commodity.

deflocculate to disperse a fine clay suspension so that particles repel each other and the substance becomes more fluid, for example, by adding a substance (a deflocculant) such as sodium carbonate that changes the electric charge of the particles. A deflocculated solution, such as a *casting* slip, tends not to settle and has a low *viscosity*; see also *flocculation*.

dehydroxylation removal of OH^- ions (chemically combined water) from the crystalline structure of *minerals*, as in the dehydroxylation of clays by application of heat.

dendrogram a treelike diagram resulting from a type of multivariate statistical analysis called cluster analysis, which depicts the mathematical relations of greater or lesser similarity between a set of entities based on their *attributes.*

density the weight of an object per unit volume, expressed as grams per cubic centimeter or pounds per cubic foot. **Apparent density** is computed from the apparent volume, that is, the true volume plus the volume of closed pores; **bulk density** refers to the overall volume including open and closed pores; **true density** is computed from true volume and excludes all pores.

design structure the layout or arrangement of a design; the way the surface area to be decorated is conceptualized, for example, whether subdivided and bounded, and the arrangement of *elements* and *motifs* within that layout.

devised classification a formal scheme of categories of entities developed by and used within a particular scientific discipline to order a set of data; compare *folk classification.*

diffraction the scattering of radiant energy (e.g., X-rays) by the edges, points, or planes of a substance, the spacings of which are comparable to the wavelength of the radiation, so that particles can be identified by such scattering.

diversity a concept in ecology that describes the structure of a population of entities by number, size, and/or proportion of constituent categories. Akin to the quantity of variance, diversity may be measured by a number of mathematical diversity indexes.

docking soaking a freshly fired article in cold water for a short period to prevent or reduce spalling of the ware if it contains calcareous inclusions.

dunting cracking that occurs in a fired ware as a result of thermal stresses. More specifically, cracking that occurs if a ware is cooled too rapidly or that appears on refiring *bisque* ware through 400–600°C, with the expansion of quartz.

earthenware a glazed or unglazed non*vitreous* ceramic material, usually low-fired, porous, and permeable, and red or brown in color. Categories include coarse earthenware (e.g., construction materials, bricks) and fine earthenwares (e.g., *majolica*).

elastic deformation temporary, reversible deformation of a material from an external force.

electron a subatomic particle with a negative electric charge. Electrons orbit the nucleus of an atom, consisting of protons and neutrons, in several distinct energy levels or shells.

element (1) a substance that cannot be decomposed into other substances; (2) chemistry: a substance all of whose atoms have the same atomic number; (3) style: the smallest component of a design that is manipulated as a single unit.

enamel a low-temperature alkali *earthenware* glaze, usually lead-based; *majolica* ware features an enamel opacified with the addition of tin.

endothermic reaction a chemical reaction that absorbs heat or requires heat in order to occur, such as the *dehydroxylation* of a clay.

engobe a slip coating applied to a *bisque*-fired ceramic body before glazing to impart a desired color or smooth texture to the surface; sometimes used synonymously with *slip.*

equivalent firing temperature an estimate of the level of firing of a ceramic (usually ancient) that takes into consideration the time and atmosphere conditions of firing

as well as temperature.

ethnoarchaeology the study of the material culture of living peoples by archaeologists to understand processes of manufacture, distribution, use, and discard and, by analogy, similar processes in the past.

exothermic reaction a chemical reaction that liberates heat, such as the burning of fuel (oxidation of carbon).

extensibility the ability of a material to be deformed without cracking or forming planes of weakness; inversely proportional to *yield point*.

fabric the composition of a fired ceramic, including clay, inclusions, and pores and excluding surface treatment; often used synonymously with *body, paste,* or *ware.*

faience (1) *earthenware* with an opaque tin-lead glaze; a French term for earthenware manufactured at the Renaissance center of Faenza, Italy; (2) a blue-green, nonpottery, glazed silicate material manufactured in Dynastic Egypt.

fall-off model see *decay model.*

felsic a *mineral* and rock with an acid composition, light colored, and high in silica.

fettle to trim rough edges, casting or mold marks, and other imperfections from dry or *leather-hard* ware before firing.

film water water that surrounds and separates platelets in a clay/water mass and makes the mass plastic; see also *shrinkage water.*

firebox the combustion chamber of a *kiln* (usually one fired by wood), typically beneath the ware chamber.

firecloud a darkened area on a vessel's surface resulting from uneven firing and the deposit of carbon in the pores during firing, characteristic of firings in which fuel and vessels are in immediate proximity.

fit the dimensional adjustment of a glaze (less frequently, of a slip) to a clay body, specifically with reference to their respective *thermal expansions* and contractions and resultant stresses, which may cause flaws in the coating.

flint a micro- or cryptocrystalline form of silica (SiO_2) containing some water and very fine pores, added to clay as an inert filler or *aggregate.*

flocculation the agglomeration or coming together of particles in a suspension, such as a slip, forming "flocs" and causing the suspension to thicken or settle.

flux a substance in a clay *body, slip*, or *glaze* that lowers the melting point of the mixture and promotes *vitrification.*

folk classification the grouping and naming of entities according to elicited native categories, as distinguished from *devised classifications.*

foot the *base* of a ceramic vessel, usually a ringlike projection formed by tooling or by adding a coil.

frit a mixture of two or more materials, fused by heating to a melt, which after rapid cooling is ground into a powder and used as an ingredient in glazes. Ingredients in a frit may be toxic (e.g., lead) without fritting.

glass a silicate mixture that has been heated to a melt and then cooled to a solid without crystallizing.

glaze a glassy coating melted onto the surface of a ceramic article, applied as a liquid suspension to a *ware* that has usually been fired once (*biscuit*) and is subsequently refired (*glost*).

glaze fit see *fit.*

glost (glost fire) glaze firing; the firing process in which a glazed ware is fired, usually having already been fired once (*bisque* firing) before application of the glaze.

green formed but unfired ceramic articles or their properties; used as greenware, *green strength*, etc.

green strength the ability of a formed and dried piece to withstand mechanical *stress* without deformation.

grog prefired clay (or potsherds), crushed or ground to small particle size and added to a clay as a type of *temper* to modify its properties.

half-life the period during which half the number of atoms in a radioactive *element* decay or disintegrate by emission of charged particles from their nuclei, thus changing into a new element.

hardness the resistance of a material to mechanical deformation, especially indentation, scratching, abrasion, or crushing affecting its surface; also the elasticity of a material.

heavy mineral an accessory detrital *mineral* present in generally small particle sizes and quantities in most rocks, and which has high specific gravity (greater than 2.89).

hue the first quality of a color corresponding to its perception as visible light as red, blue, green, etc.; in *Munsell* nomenclature, hue refers to different pages or sheets corresponding to radii of the color cylinder model.

hygroscopic the ability or tendency of a material (e.g., CaO) to take up moisture readily from the surrounding air or other moist materials.

illite a group of clay minerals having a three-layer, nonexpanding structure similar to that of well-crystallized micas.

inclusion particulate matter, usually *mineral* in nature, present in a clay or fabric either naturally or added by the potter; often used synonymously with *temper.*

interaction hypothesis the proposition that the similarity (or frequency) of decorative elements shared between social groups is proportional to the direction and intensity of interaction between those groups.

interlayer water water that exists between the unit layers of the three-layer (or 2:1) clay minerals; the last water to be lost in drying.

intrinsic properties properties of a ceramic affecting its performance, including *modulus of elasticity*, Poisson's ratio, modulus of rupture, *thermal conductivity*, and *thermal expansion.*

inversion a transformation or change of phase, typically in a solid, from one polymorphic form to another with different atomic structure and bonding; see also *quartz inversion.*

ion an atom or group of atoms with an electrical charge, either positive (cation) or negative (anion).

isotopes nuclides or *elements* having an identical number of protons in their nuclei but differing in their number of neutrons. The isotopes of an element have different atomic weights (mass), very similar chemical properties, and identical atomic structures.

isotropic having the same properties in all directions, usually with reference to optical properties but also pertaining to physical properties such as shrinkage.

jigger to form an article of ceramic flatware by means of a rotating mold and profile tool; the machine by which such a process is accomplished. Usually the mold has the contour of the interior and the profile tool has the contour of the exterior surface, but sometimes the term is used interchangeably with *jolly* without specifying the article formed or which surface is shaped by which apparatus.

jolly (jolley) to form ceramic hollowware by a machine similar to a *jigger*, but the rotating mold forms the outside while a profile tool forms the interior.

kaolinite a common clay mineral having a two-layer structure of silica and alumina and the ideal chemical composition $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$; the principal mineral of the kaolin clay (also called *china clay*) group.

kiln an enclosed or partially enclosed chamber(s) for firing ceramic materials. Kilns may be classified on the basis of characteristics of construction, firing

characteristics, or products.

lattice structure see *crystal*, *crystalline structure*.

lattice water see *crystal lattice water.*

leather-hard clay that is dried to the *critical point* so that individual clay particles touch and the body is rigid, but retaining sufficient moisture to be carved or joined.

levigation separating fine from coarser material, such as clays, by mixing with a liquid (water) and washing down a series of traps, allowing the coarser material to settle.

lime popping (lime blowing) a surface defect on ware containing inclusions of calcium *carbonate* ($CaCO_3$, as limestone, shell, or calcite). When fired to temperatures between about 650°C and 900°C, the inclusions decompose and after cooling the lime (CaO) rehydrates with an accompanying expansion.

lip the edge or margin of the *orifice* of a vessel; sometimes refers more specifically to a modification of a *rim* of a vessel for pouring.

lute to join together two *leather-hard* pieces of a vessel by using *slip* as a glue.

mafic a *mineral* or rock with a basic chemical composition, dark-colored and high in ferromagnesian (Fe; Mg) minerals.

magnetism a property or force field that causes certain materials to attract other materials. The property, of which there are several kinds, results from the spin of *electrons* in the materials' atoms (electric charge).

majolica (maiolica) *earthenware* covered with an opaque tin-lead *enamel*, best known from fifteenth- to nineteenth-century Europe. Delft ware and *faience* are two types of tin-enameled earthenwares that fall under the rubric majolica.

marl a calcareous clay; a mixture of clay and particles of calcite, dolomite, and/or shell.

maturity the range of temperature and time (the maturing range) at which a clay body fires to desired qualities of *hardness*, *porosity*, and serviceability; the temperature and time at which a glaze develops qualities of bonding (to the body), stability, strength, and texture.

metakaolin *dehydroxylated* kaolin, formed after firing *kaolinite* above approximately 500°C. Metakaolin is nonplastic and has lost most of its *crystalline structure*, but it can rehydrate and revert to kaolinite.

metal in geochemistry, an *element* that gives up the electrons in its outer orbit, forming *cations*, and combines with oxygen to form basic *oxides*; aluminum (Al) is a metal.

microstructure the arrangement of *phases* of a material; in a ceramic, the internal arrangement of crystalline and amorphous materials, pores, and boundaries between them, which underlies use-related properties.

mineral a homogeneous, inorganic, naturally occurring solid with a characteristic chemical composition and a crystalline (regularly ordered) atomic structure.

mode a classificatory term referring to *attributes* (of a set of artifacts) that are judged to be behaviorally and culturally significant as reflections of common standards for the manufacture and use of the artifacts.

modulus of elasticity (*E*, or Young's modulus) a measure of the rigidity of a material or its ability to withstand mechanical *stress* without deformation. Ceramics typically have high *elastic* moduli.

Mohs' scale an ordinal *hardness* scale developed in the nineteenth century for *minerals*, consisting of a series of increasingly hard minerals from 1 (talc) to 10 (diamond). The minerals in the scale are drawn across the test piece to determine which mineral is sufficiently hard to mark the ceramic, thus measuring *scratch hardness.*

molecule two or more atoms held together by chemical bonds; water (H_2O), for example, exists as molecules.

montmorillonite a common clay mineral of the *smectite* group, having a small particle size and an expanding lattice.

motif a fixed combination of design *elements* that forms a larger component of the decoration.

mouth the *orifice* or opening of a hollowware vessel.

Munsell charts a series of charts published by the Munsell Color Company for the standardized identification and description of colors; color is divided into three components, *hue, value,* and *chroma,* and individual *shades, tints,* and *tones* are represented by rows of small color chips.

neck the part of a vessel between the *shoulder* and the *rim,* typically characterized by a marked constriction of the maximum body diameter; where there is little constriction, the region is often called a *collar.*

nonmetal in geochemistry, an *element* that gains or shares electrons in its outer orbit and forms acidic *oxides.*

nonplastic material in a clay, whether naturally present or added by the potter, *mineral* or organic, which by virtue of generally large particle size lacks the property of plasticity and often reduces the plasticity and stickiness of the clay; see also *additive, aggregate, aplastic, grog, inclusion, temper.*

orifice the *mouth* or opening of a vessel, usually hollowware.

oxidation the combining of an atom or ion with oxygen, usually resulting in the loss of electrons; a firing atmosphere characterized by an abundance of free oxygen, which combines with *elements* (such as iron) in the body and yields clear colors of the ceramic body; see also *reduction.*

oxide a compound of oxygen plus another *element*.

paint the action of applying a *colorant* (not the *pigmenting* material itself).

palygorskite a group of hydrous-magnesian clay minerals characterized by a distinctive rodlike or needlelike shape related to chaining rather than a sheetlike arrangement of atoms. Palygorskite is related to *attapulgite* but magnesium is replaced by aluminum.

parting agent a material, such as sand, ash, or dry clay, sprinkled over a mold or working surface to prevent wet clay from sticking.

paste a clay or mixture of clay and added materials, often used synonymously with *fabric*, *body*, or *ware.* Technically paste differs from *fabric* because it does not include *pores* and differs from *ware* because it excludes surface treatment.

pattern any design with regularly repeated parts; roughly synonymous with *symmetry* as a type of analysis of pottery design.

permeability the capacity of a material to transmit a fluid, measured as the amount of liquid passing through a given thickness in a given time.

petrography the microscopic study and description of rocks or other *mineral* material (such as ceramics) by their optical properties; see *polarizing microscope*.

petrology the study of the natural history of rocks, including their origins, alterations, and decay, and description of their present condition.

pH the relative alkalinity or acidity of a solution, measured as the negative logarithm of hydrogen *ion* activity (or concentration).

phase a homogeneous, physically distinct (bounded) portion of a nonhomogeneous system. Phases in ceramics include individual grains, glassy material, and pores.

phyllosilicate a layered *silicate mineral*; the major category of clay minerals, composed of those with a regular ordering of layers of silica and alumina structural components.

pigment a coloring material, usually a mixture of *colorants,* clay, water, and a *binder*; may be organic or inorganic.

plagioclase one of several soda-lime feldspar *minerals*, a common rock-forming mineral group.

plastic deformation stress exceeding the *elastic* limit, causing permanent shape distortion.

plasticity the property of a material, such as a clay, that enables it to be shaped when wet and to hold this shape when the shaping force is removed.

plasticity, water of the water required for a clay material to develop optimal *plasticity.*

plastic limits the range, often subjective, in the amount of water that may be added to a dry clay in order to develop a satisfactorily plastic mass; see also *working range.*

point count a method of determining the quantity of grains or *inclusions* in a material by counting individual grains of different *phases* along a line (or within a transect) as the specimen is viewed in a microscope.

polarizing microscope (petrographic microscope) a microscope that incorporates filters to modify the vibration direction of light as it passes through a thinly ground section of a *mineral* and permits characterization of that mineral by its optical properties; see *birefringence*, *refractive index*.

polish a glossy luster on the surface of an unglazed ceramic article, produced by rubbing it while *leather-hard* with a yielding tool; lacks the individual parallel facets characteristic of *burnishing.*

porcelain a fine, *vitrified*, high-fired ceramic body, usually translucent and white, used for pottery or various industrial and scientific products.

pore water mechanically combined water remaining in the pores and capillaries of a clay article after shrinkage is completed and particles come into contact with each other.

porosity the volume of pores contained within a solid, such as a ceramic object, measured as *true* or *apparent porosity.* In most pottery studies open or apparent porosity is measured.

pottery low-fired, nonvitrified objects including cooking, serving, and storage vessels (as distinct from high-fired *ceramics*); one of several industries within the ceramic field, including manufacture of tableware, utensils, and tiles.

precision the dispersion of a set of measured values; the reproducibility of a technique.

preferred orientation a systematic orientation of platy or acicular crystals in which the crystals are aligned parallel to their long axis.

primary clay (residual clay) a clay deposit located on its geological site of formation by weathering from a parent rock (as opposed to a *secondary* or transported clay).

profile a type of illustration of ceramic objects based on the vertical cross section, showing wall thickness and details of lip, rim, and base.

props shelf supports for kilns, made of *refractory* material.

provenance see *provenience*.

provenience (1) the specific recovery location or archaeological findspot of an artifact; (2) the geospatial location of production of an artifact; (3) the geological raw material source(s) of an artifact (also provenance); (4) an analysis carried out with the aim of discovering such sources and origins, usually by chemical and/or mineralogical *characterization* of the composition of the artifacts in question and comparison with raw materials or known products in a particular area of interest.

pyrometric cones see *cones*.

quartz inversion a change in the atomic structure and bonding of quartz during heating. One inversion (from **α** to **β**) occurs at 573°C, the second (to tridymite) at 867°C, and the third (to cristobalite) at 1250°C.

reduction (reducing atmosphere) a chemical reaction characterized by addition of electrons (as contrasted with *oxidation*); an atmosphere of firing in which oxygen is removed from substances or materials, for example, because of reducing agents such as hydrogen, carbon, or carbon monoxide.

refractive index the ratio of the velocity of light in air to its velocity in a given medium, such as a *mineral*, which bends or refracts the light and thereby changes its direction and velocity.

refractory ceramic materials, usually high in alumina and silica, that can withstand high temperatures and are slow to melt.

residual clay a clay deposit near the parent rock from which it weathered; a *primary clay* as distinguished from a *secondary clay.*

rilling the spiral ridges or striations around the interior or exterior surface of a vessel *thrown* on a *wheel*, formed by finger pressure in "lifting" the clay; also called throwing marks.

rim the area between the *lip* or margin and the side wall or *neck* of a vessel; sometimes used interchangeably with lip, especially if there is no change of orientation between the lip and neck or wall.

ring building a type of *coiling* in which individual coils or annular rings are placed as separate "courses" to build a vessel.

saggar (sagger, seggar) a container made of *refractory* clay used to protect clay articles and glazes from flames and gases during firing.

sampling the process of selecting a small number of units from a larger whole, called the population.

sand a particle size grade ranging from 2 mm to 0.05 mm in diameter; often incorrectly used to refer to the composition of a detrital sediment, especially one composed of quartz.

scratch hardness a measure of relative hardness of pottery, obtained by comparison with *minerals* of known hardness (*Mohs' scale*). A mineral harder than the pottery will scratch it, but it will be unmarked by a mineral that is less hard.

secondary clay a clay deposit moved away from the original parent from which it weathered by various natural forces and redeposited; a sedimentary or transported clay, contrasted with a *primary* or *residual clay*.

sensitivity the limits of detection of an analytical technique, such as a chemical analysis, phrased as either the smallest quantity of material detectable or the lowest atomic number of elements that can be analyzed.

sepiolite a clay mineral with a spongy, fibrous, or lathlike structure related to *palygorskite*; meerschaum.

seriation one of several techniques archaeologists use to determine the similarity of artifacts or sets of artifacts and then to place them in a series, their order typically being interpreted as relative age.

shade a variation of a color produced by adding black.

shear a type of *stress* caused by simultaneous application of opposing forces, causing parts of a clay body to slip or slide relative to each other.

sherd (potsherd, shard) a term archaeologists use to refer to a broken fragment of pottery.

shivering a defect caused by compressive *stress*, resulting in incomplete coverage or peeling of the *glaze.*

shoulder the upper part of the body of a restricted vessel; that portion between the maximum diameter and the *orifice* or *neck.*

shrinkage water the portion of mechanically combined water that separates the clay particles in a clay/water mass and, when lost during drying, contributes to shrinkage of the body; see also *film water.*

silicate a compound in which SiO_4 tetrahedrons are major constituents. Clays, for example, are alumina-silicates in which the tetrahedrons are joined primarily as sheets.

silt a particle size grade in which particles are between 0.05 and 0.002 mm in diameter; a sediment consisting of 80% or more silt-sized particles and less than 12% *clay*-sized particles.

sinter a process of adhesion and densification (but not complete fusion or *vitrification*) of a particulate material upon heating close to but below the melting point.

skeuomorph an object made of one kind of material, such as pottery, that imitates in shape and decorative detail objects made of other materials, such as metal, wood, leather, or gourd.

slip a fluid suspension of fine clay and water, used to coat a body before firing or poured into a mold to cast a piece; a non*vitreous* coating on a pottery vessel; see also *engobe.*

smectite a group of clay minerals having a three-layer structure consisting of two silica layers with an alumina layer between, characterized by expandability and relatively high *base exchange*. Common smectite clay minerals include *montmorillonite*, bentonite, and saponite.

soak, soaking period the time during which the highest temperature of firing is sustained.

specialization the practice of a particular economic activity by a relatively small number (as compared with total output or market) of skilled individuals who engage in it for their primary livelihood.

spectrometry methods of chemical characterization based on analysis of the electromagnetic spectrum of radiant energy emitted by the sample (emission spectrometry) or absorbed by it (absorption spectrometry) under specified conditions.

spur kiln furniture consisting of triangular supports placed to prevent glazed ware from sticking to shelves of the kiln in firing; sometimes called *stilts* or trivets.

stain a prepared, *fritted* compound of coloring *oxides,* alumina, and a *flux* used as a glaze *colorant* or for overglaze and underglaze decoration.

standardization a reduction, over time, of variation in *attributes* of composition, form, and style within a particular category of artifact, such as pottery.

stilt kiln furniture consisting of small clay tripods used for holding glazed ware in a kiln; sometimes called *spurs* or cockspurs.

stoneware a *vitreous* or semivitreous ceramic ware, usually gray, brown, or white, and frequently glazed.

strain *elastic* deformation response to *stress* forces: change in dimension per unit dimension.

strength toughness, or resistance to *stresses* affecting the body, as opposed to the surface (*hardness*), of a ceramic.

stress an applied force, measured per unit area. Significant stresses in ceramics include *tensile*, *compression*, *transverse*, and impact stresses.

style (1) a manner or mode of expression or the character of that expression; (2) a visual representation, specific to a particular time and place, that transmits information about the identity of the makers and the context of use. Style usually refers to decorative or surface embellishment, but it may also refer to a constellation of technological traits.

symmetry a property of design based on the spatial position of the geometric figure(s) constituting the fundamental part of the design, and on the movement of the figure(s) across a line or around a point axis (e.g., translation, reflection, rotation, and slide reflection).

taxonomic classification a formal *classification* scheme, often hierarchical (e.g., the *type-variety system*), that specifies inclusion relations and results in the creation of *types*.

temper to mix or modify to a proper consistency; a material—*mineral* or organic, but usually nonplastic—added to a clay to improve its working, drying, or firing properties; see also *additive, aggregate, aplastic, grog, inclusion, nonplastic.*

tensile strength the ability of a material such as a ceramic to withstand a tensile load, or stresses or elongation (extension) forces. Ceramics have low tensile strength.

terracotta an *earthenware* body, unglazed, usually red, relatively coarse and porous, and low fired; sculptural or architectural articles made from such an earthenware body.

terra sigillata a red-slipped earthenware associated with Roman Europe. Although the name means “stamped” (from *sigillum*), the term is used by studio potters to refer to a red earthenware slip or “slip glaze” having the same properties as its ancient counterpart.

texture (1) the proportion, size, shape, and orientation characteristics of *phases* in a clay body; (2) the general character of a fired *fabric* as viewed in cross-section, described in terms of particle size (fine vs. coarse), characteristics of fracture (friable, blocky), and density (dense vs. porous); (3) sometimes, the surface quality of a vessel.

thermal conductivity (*k*) the ability of a material to conduct heat, measured as the rate of heat flow through unit area per unit temperature gradient.

thermal expansion the change in size (length or volume) of a material with increasing temperature of firing; see also *coefficient of thermal expansion.*

thermal fatigue the delayed failure of a ceramic as a consequence of thermal stress, caused by the cumulative effect of repeated cycles of heating and cooling.

thermal gradient a temperature differential between the surfaces and interior of the walls of a vessel that may exist during firing, cooling, or use with heat; also from top to bottom in a kiln.

thermal shock resistance the ability of a ceramic object to withstand sudden changes in temperature or repeated cycles of heating and cooling (*thermal stress*) without damage.

thermal stress internal *stresses* in a ceramic body arising from repeated subjection to temperature changes and the resulting thermal expansion and contraction of the components in the body.

thin section a piece of rock or ceramic, ground to extreme thinness (0.03 mm) and mounted between glass slides, usually for study in a *polarizing microscope.*

throat the base of a *neck* or *collar* on a vessel, or the point of maximum diameter restriction of a neck or collar.

throw to form a ceramic object on a potter's *wheel*, making use of the centrifugal force produced by rapid, sustained rotation of the wheel.

tint a variation of a color produced by adding white to it, characterized by low saturation.

tone a mixture of light (white) and shade (black) with a color.

tournette a small pivoted turntable used as a revolving support for hand building vessels, but lacking the weight for sustained rotation and the centrifugal force for *throwing* on the true potter's *wheel.*

trace elements an *element* present in very small amounts in the earth's crust (in amounts less than 0.1%). Elements present in amounts less than 1 ppm are sometimes called ultratrace.

transition element an *element* in the middle of the long periods (rows) of the periodic table, many of which (especially Ti, V, Cr, Mn, Fe, Co, Ni, and Cu) are important coloring agents in *glazes*.

transverse stress flexural stress; a stress or force causing bending.

triaxial body a modern prepared clay body consisting of a clay, an *aggregate* or filler (e.g., *flint* or *grog*), and a *flux.*

true porosity total porosity; the total proportion of the bulk volume of a material occupied by pores, both open and closed. True porosity cannot be easily measured in a ceramic, and usually *apparent porosity* is measured.

type a nonrandom cluster of attributes; an internally cohesive class of items formally defined by a consistent association of *attributes* (or *attribute states*) and set off from other classes by discontinuities in attribute states.

type-variety system a standardized system of pottery *classification* that defines a hierarchy of increasingly inclusive classes, from varieties (minimal units) through *types* and groups, to *wares.*

typology a theoretically oriented classification directed toward solving a problem; see also *classification.*

underglaze a type of colored decoration applied to raw or *biscuit* ware before the *glaze* coating is applied.

value the intensity, brilliance, or lightness/darkness of a color. In the *Munsell* system, value is the vertical dimension, varying from dark to light.

variable see *attribute*.

viscosity the resistance of a fluid to *shear* or flow; the thickness or stiffness of a fluid (such as a slip or glaze) causing it to resist being stirred or to not flow (run) once applied to a body.

visible spectrum that portion of the range of energies (vibrations or wavelengths) of the electromagnetic spectrum that is perceived by the human eye as visible light, generally defined as consisting of wavelengths of 400 to 700 μm.

vitreous glass-like; see *vitrify*.

vitrify, vitrification the action or process of becoming glass; the high-temperature process whereby the particles within a mass fuse, closing the surface pores and forming a homogeneous, impervious mass without deformation.

void an open space in a pottery fabric; pore.

volatilize vaporize; to convert to a vapor or to the state of a gas, as with the heat of firing.

ware a ceramic material in the raw or fired state (*green* ware, *earthenware, stoneware,* etc.); a class of pottery whose members share similar firing technology, composition, and surface treatment, or some combination of these.

waster vessels or sherds from vessels damaged in manufacturing, particularly in firing, as by overfiring, underfiring, warping, or bloating.

water of plasticity see *plasticity, water of.*

water smoking preheating; the initial phase of the firing cycle in which all mechanically held water in the clay piece is *volatilized* and removed by slow heating to about 120°C.

wedge to knead or mix a plastic clay body with the hands or feet, or to cut and rejoin the mass before kneading, to eliminate air pockets, randomize the orientation of particles, compress the mass, and provide a uniform distribution of moisture.

wheel (potter's wheel) a pivoted device capable of sustained rotation (usually by means of a flywheel) upon which a potter builds or *throws* a vessel making use of centrifugal force produced at high rotation speeds to aid in lifting and shaping the piece to its final form. May be driven mechanically (by kicking or by turning with a stick) or electrically.

work heat (ratio) the effect of a particular amount of heat in a particular amount of time on the firing of a ceramic, registered by pyrometric *cones* but not by temperature alone.

working range the variable amounts of water that may be added to a dry clay to make it satisfactorily plastic; see also *plastic limits.*

yield point the force or stress at which deformation or flow begins to take place in a clay/water system; inversely proportional to *extensibility*.

Young's modulus (*E*) a measure of the rigidity of a material; see also *modulus of elasticity.*

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Notes

Note to Chapter 1

1 Dates, ages, and times reported here are generally those given in the works cited. There is, unfortunately, very little consistency in how radiocarbon assays are presented in publications (see Kuzmin 2006): they may be calibrated or uncalibrated, corrected or uncorrected, as ages or dates, in radiocarbon years or calendar years, before present (bp/BP), before Christ (bc/BC), or before the common era (BCE), with or without standard deviation (1- or 2-**σ** range) or percent probabilities, or combinations of these. A generally accepted convention is to distinguish calibrated dates/ages as "cal. BP" or "cal. BC" and uncorrected/uncalibrated ones by lowercase bp/bc.